Safety Benefits of the 18650 Bottom Vent for Future Space Battery Applications

By

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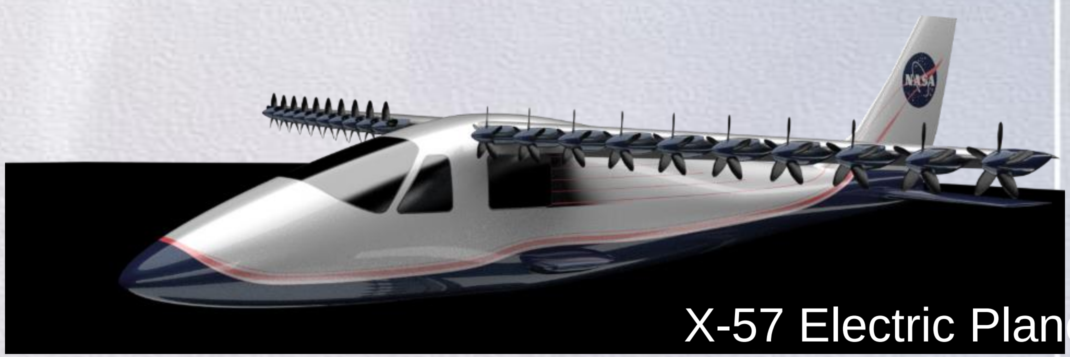
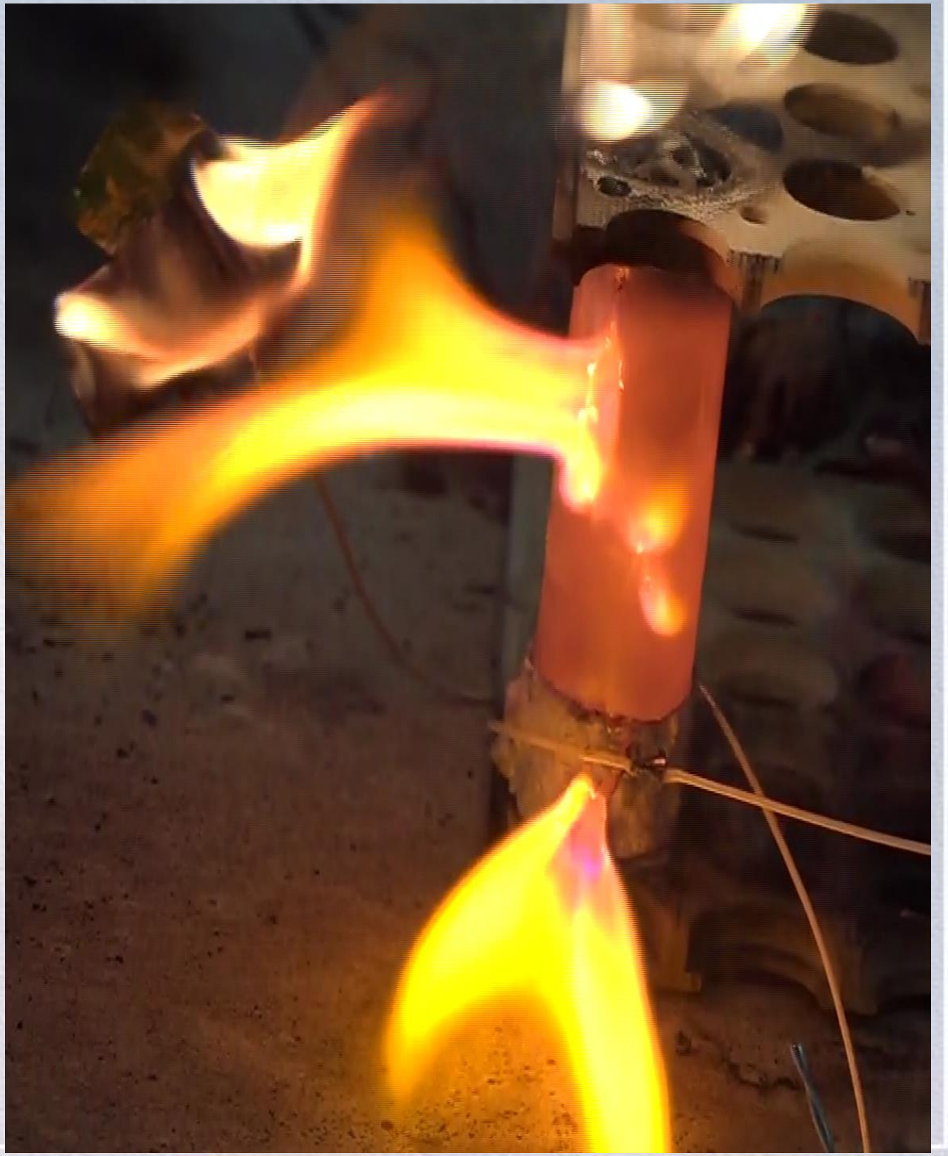
NASA's Future Applications

- Robonaut 2
  - To enhance and reduce frequency of manned spacewalks
  - High energy density and high specific energy battery needed
  - 90V, 4 kWh, 7 hour mission
- Mars Rover Vehicle
  - Terrestrial demonstration vehicle needing high voltage, power battery
  - 400V, 4 kWh, 1 hour mission
- Valkyrie, RoboSimian
  - Terrestrial dangerous operations robot
  - 90V, 2kWh, 1 hour mission
- X-57 Electric Plane
  - All electric aircraft for flight training
  - 400V, 50 kWh, 1 hour mission



5 Design Driving Factors for Reducing Hazard Severity from a Single Cell TR

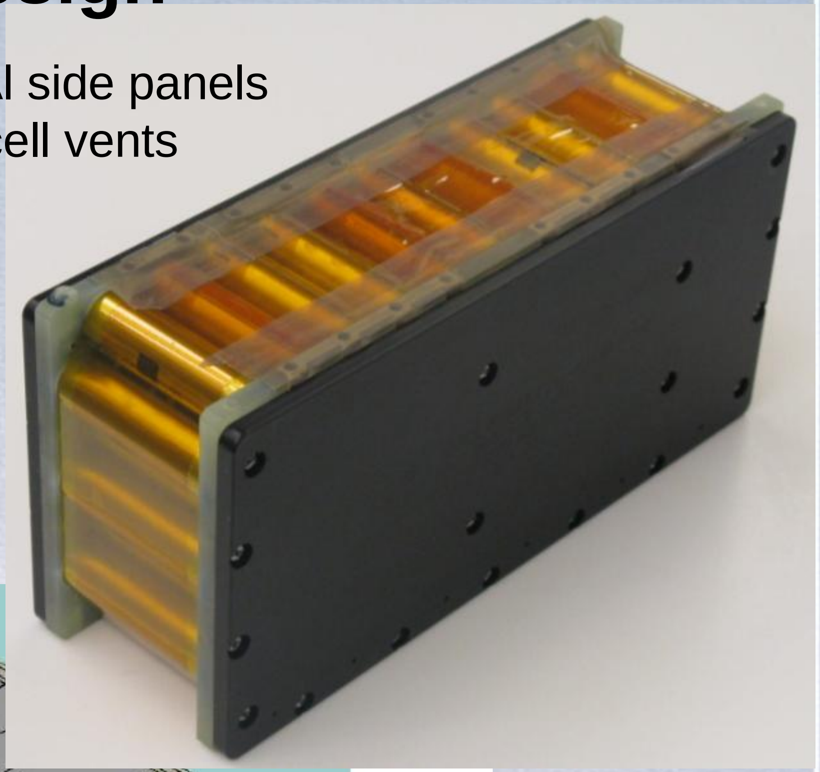
- Reduce risk of cell can side wall ruptures
  - Without structural support most high energy density (>600 Wh/L) designs are very likely to experience side wall ruptures during TR
- Provide adequate cell spacing
  - Direct contact between cells without alternate heat dissipation paths nearly assures propagation
- Individually fuse parallel cells
  - TR cell becomes an external short to adjacent parallel cells and heats them up
- Protect the adjacent cells from the hot TR cell ejecta (solids, liquids, and gases)
  - TR ejecta is electrically conductive and can cause circulating currents
- Prevent flames and sparks from exiting the battery enclosure
  - Provide tortuous path for the TR ejecta before hitting battery vent ports equipped flame arresting screens

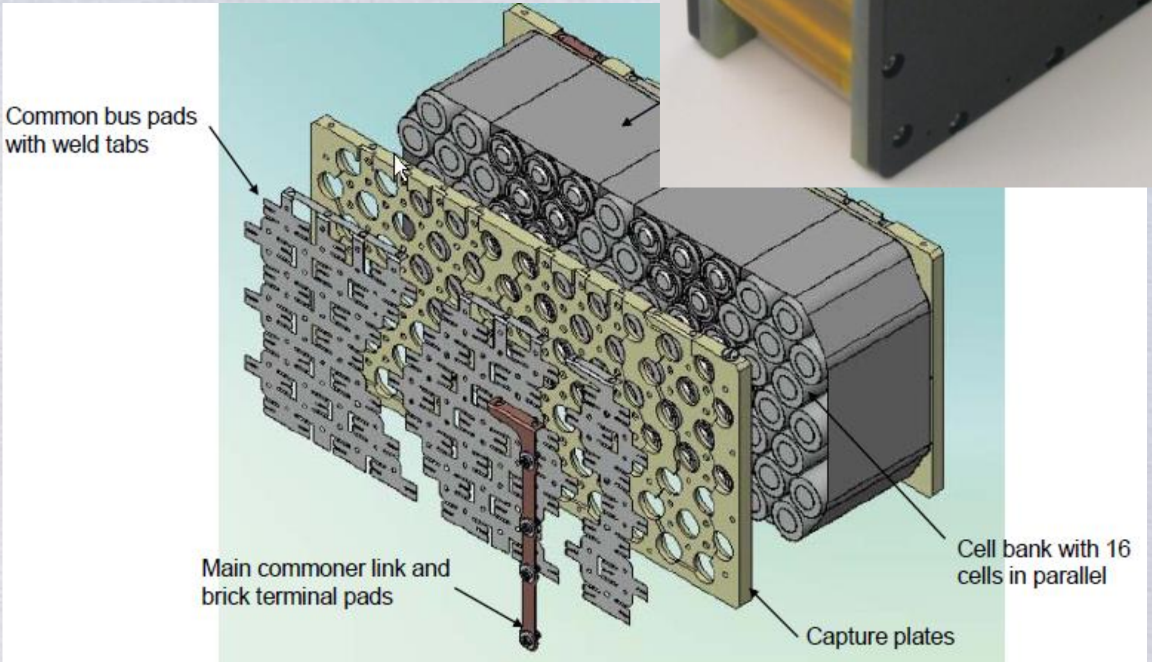


Current Spacesuit Battery Design

Design Features
- 80 Li-ion cells (16p-5s)
- ICR-18650J from E-one Moli Energy (2.4Ah)

Solid Al side panels block cell vents





<u>Compliance with the 5 rules</u>
- Minimize side wall ruptures ✓
- No direct cell-cell contact ✓
- Individually fusing cell in parallel X
- Protecting adjacent cells from TR ejecta X
- Include flame arresting vent ports X

Design Propagates TR – Catastrophic Hazard

No place for the cell TR effluent to vent

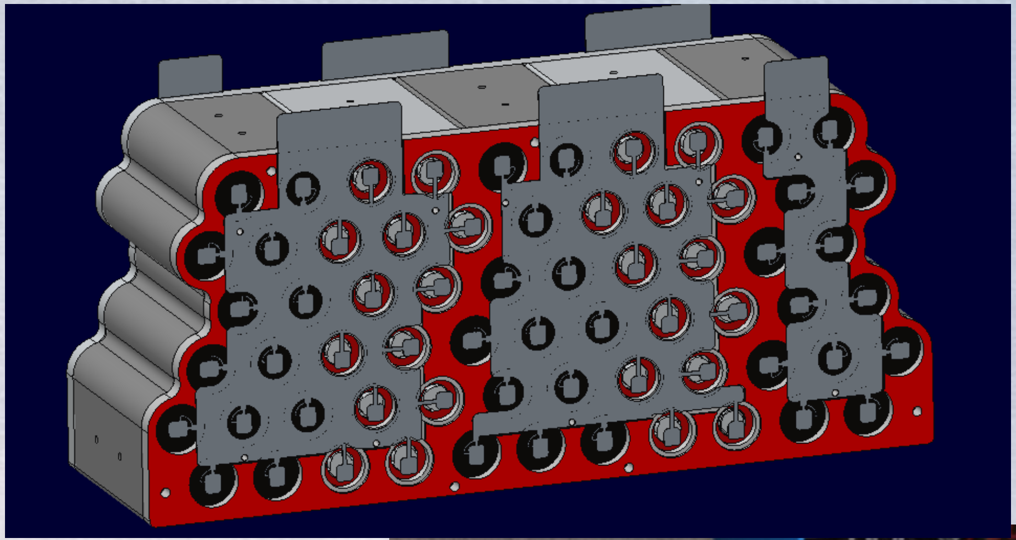
Safer, Higher Performing Battery Design

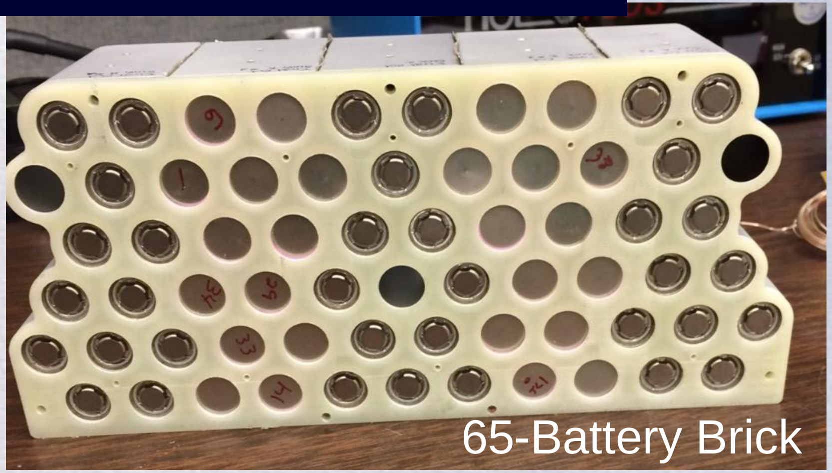
<u>Compliance with the 5 rules</u>

- **Minimize side wall ruptures** ✓
  - Al interstitial heat sink
- **No direct cell-cell contact** ✓
  - 0.5mm cell spacing, mica paper sleeves on each cell
- **Individually fusing cell in parallel** ✓
  - 12A fusible link
- **Protecting adjacent cells from TR ejecta** ✓
  - Ceramic bushing lining cell vent opening in G10 capture plate
- **Include flame arresting vent ports** ✓
  - Tortious path with flame arresting screens
  - Battery vent ports lined with steel screens

Features

- 65 LG (INR18650 MJ1) 3.5Ah cells (13P-5S)
- 37Ah and 686 Wh at BOL (in 16-20.5V window)
- Cell design likely to side wall rupture, but supported



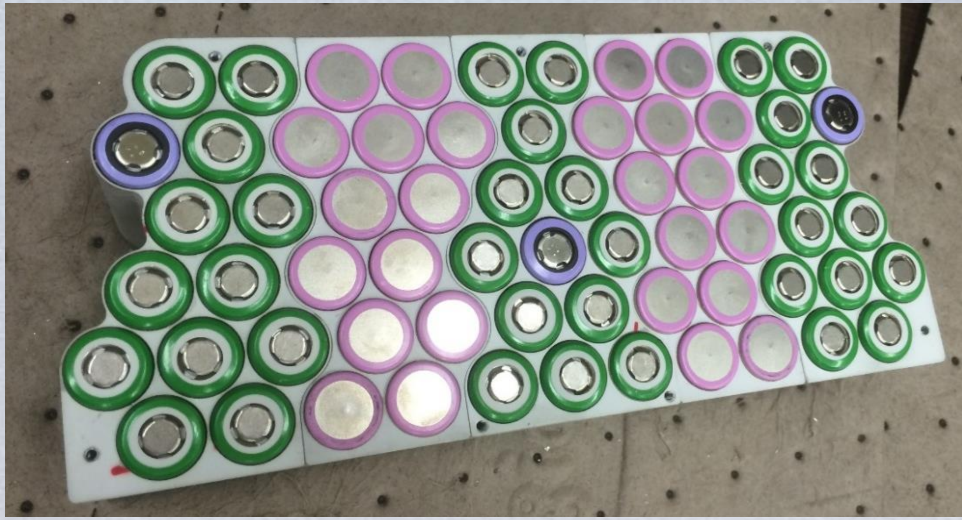


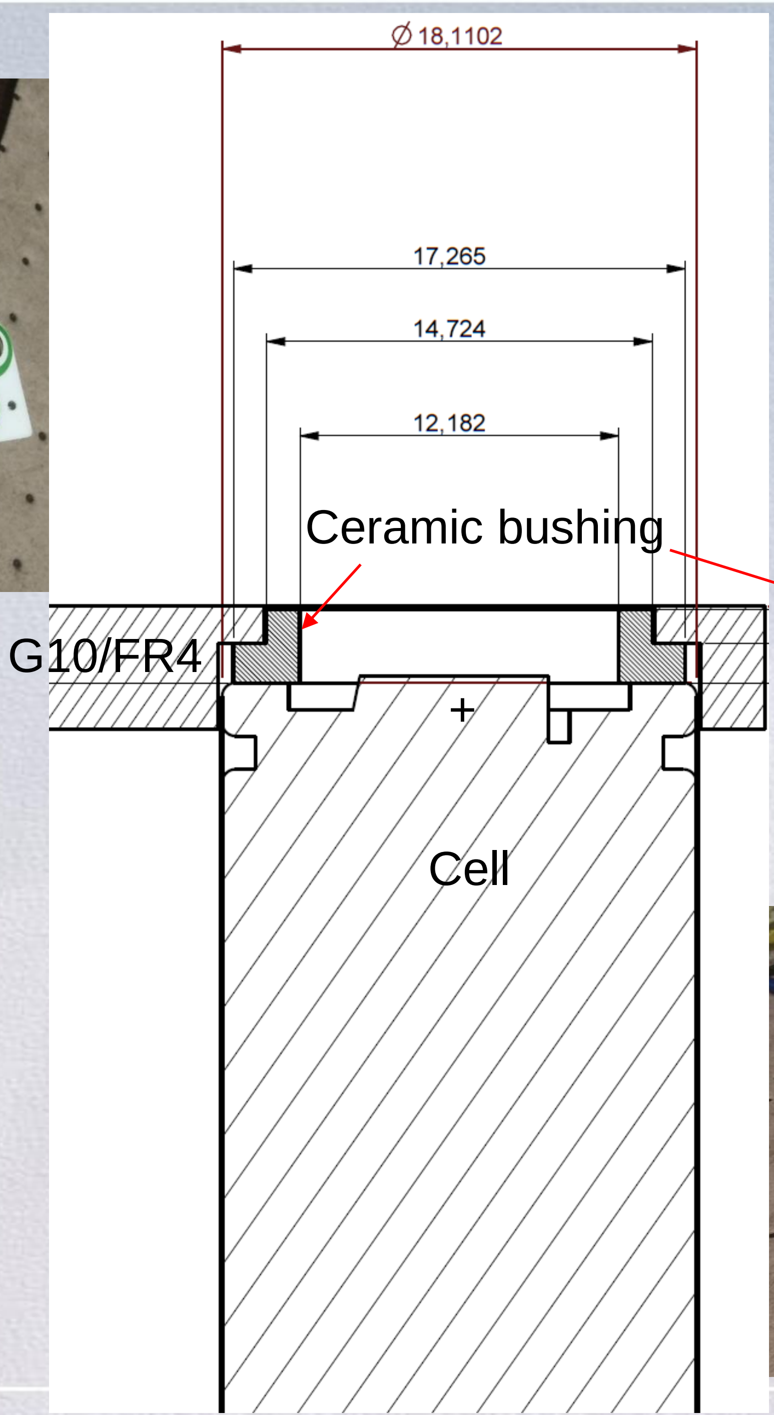
65-Battery Brick

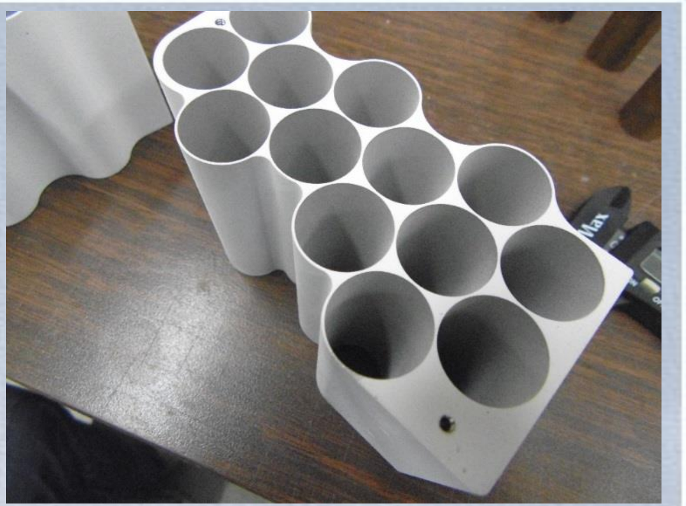
LLB2 Heat Sinks

No corner cells - Every cell has at least 3 adjacent cells

0.5mm cell spacing, Al 6061T6



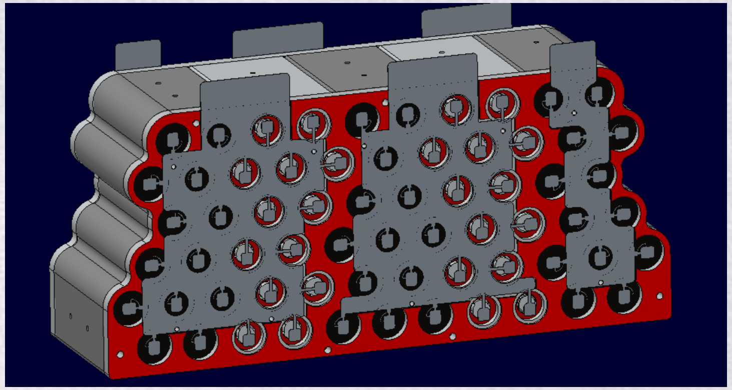




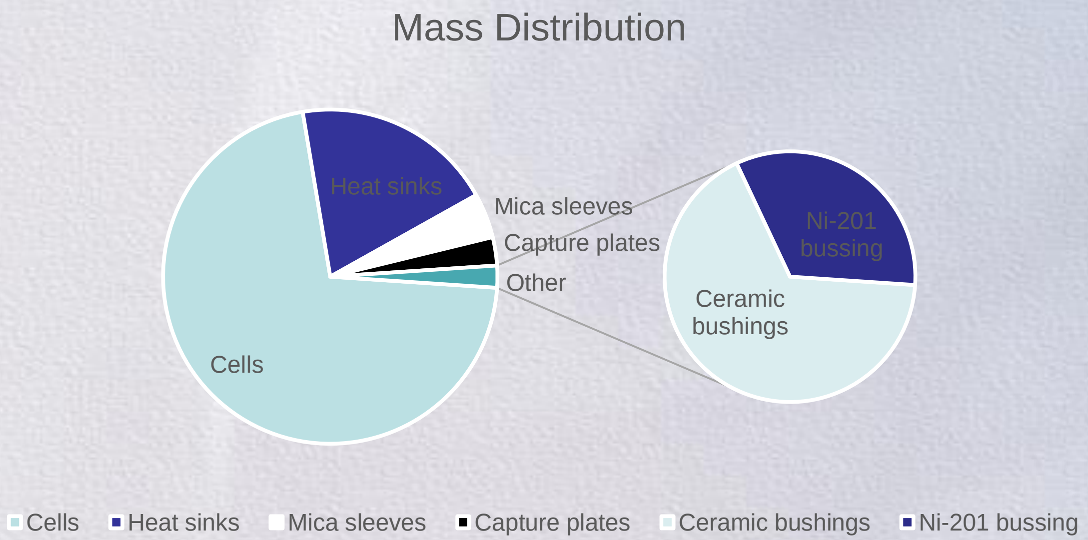
- 13P-5S Configuration with 3.5 Ah LG INR MJ1 cells. 37 Ah at 3.8 A mission rate.
- Aluminum interstitial heat sink, 0.5 mm spacing between cells
- Mica sleeves around shrink wrap, 2 FT
- The G10 capture plate houses the + and - ends of the cells and prevents the Ni bussing from shorting to the heat sinks.
- The ceramic Macor bushing acts as a chimney to direct ejecta outwards and protect the G10/FR4 capture plate

Cell Brick Assembly > 180 Wh/kg

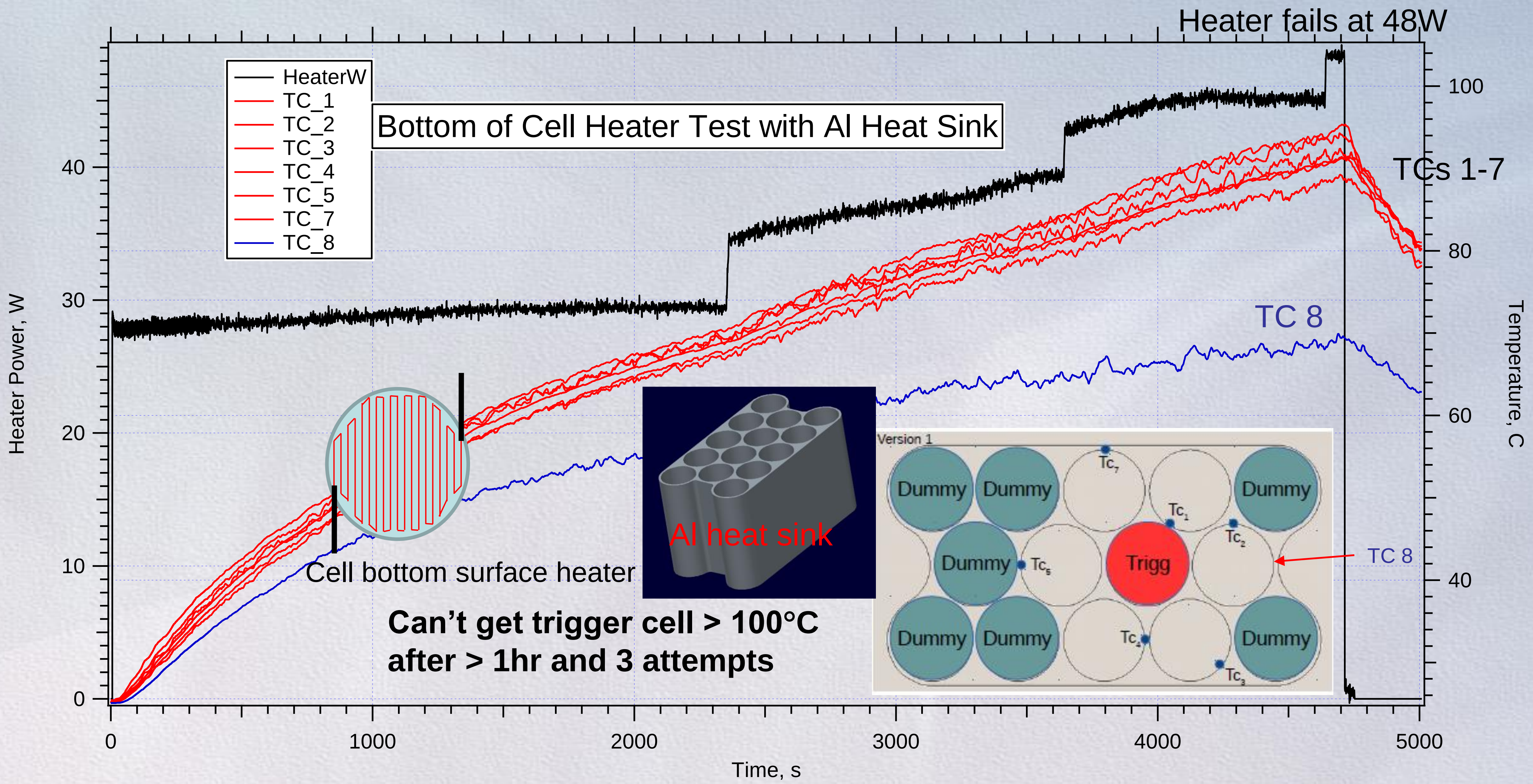
Mass Categories	g	%
LG MJ1 Cells	3012.75	71.3%
Heat sinks	824.95	19.5%
Mica sleeves	182.31	4.3%
Capture plates	115.81	2.7%
Ceramic bushings	60.15	1.4%
Ni-201 bussing	29.71	0.7%
Total	4225.7	



- With 12.41 Wh/cell, cell brick assembly achieves 191 Wh/kg
  - Assuming 12.41Wh per cell
- Design has 1.4 parasitic mass factor
  - – Cell mass x 1.4 = Brick mass

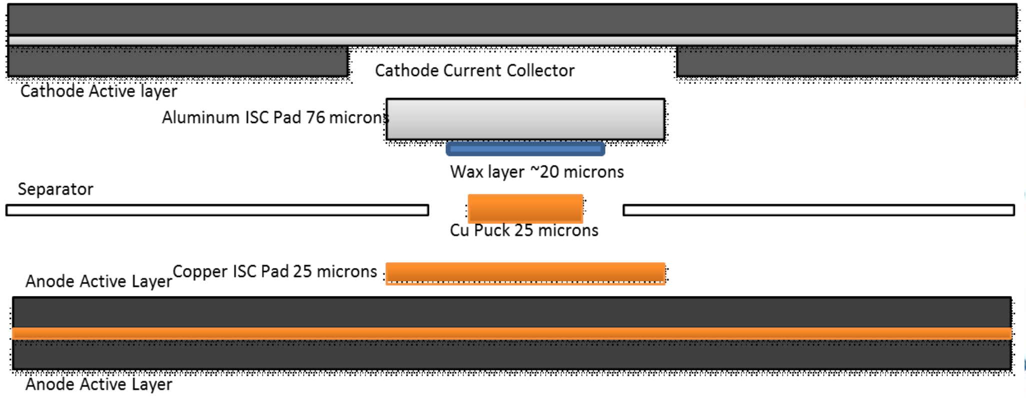


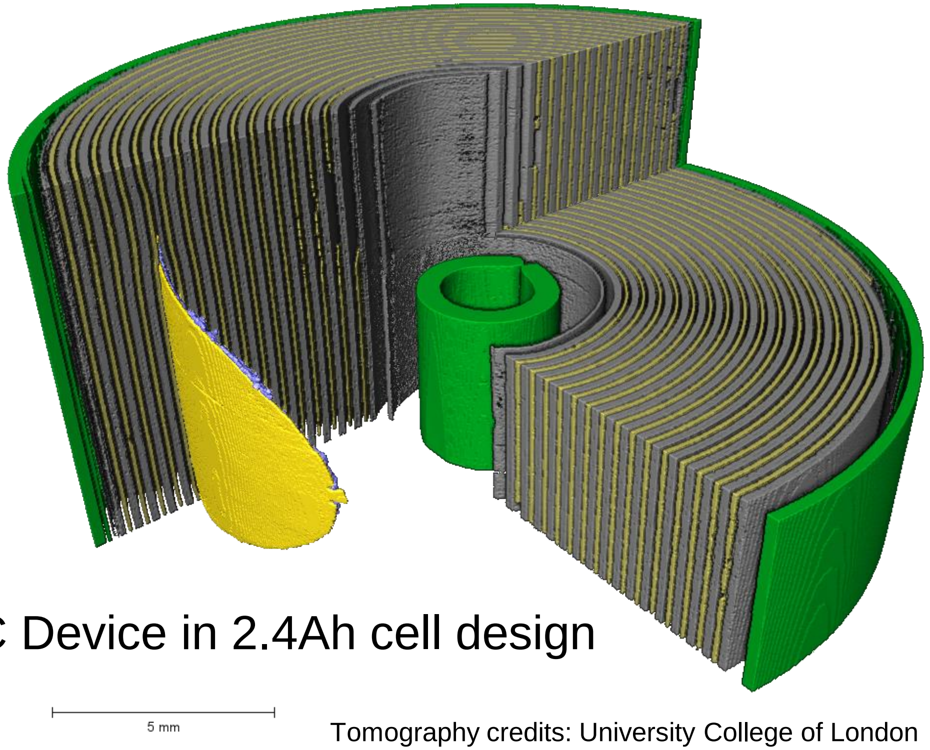
Attempts to Drive TR with Cell Bottom Heater Fails



NREL/NASA ISC Device Design

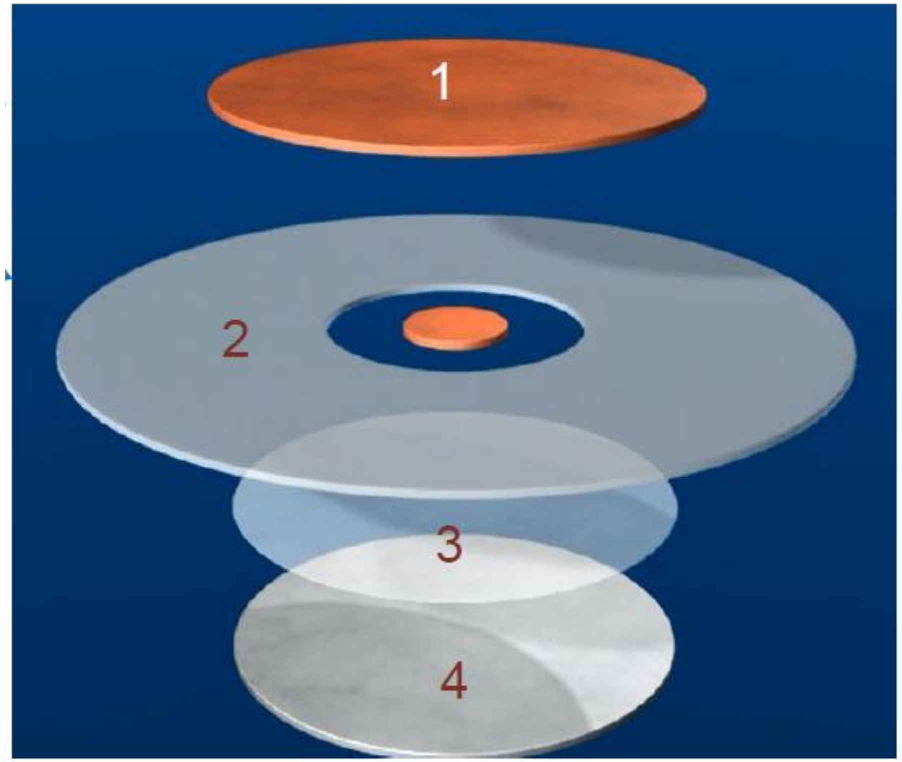
Active anode to cathode collector short





ISC Device in 2.4Ah cell design

Tomography credits: University College of London



Graphic credits: NREL

Top to Bottom:
1. Copper Pad
2. Battery Separator with Copper Puck
3. Wax – Phase Change Material
4. Aluminum Pad

2010 Inventors:
- Matthew Keyser, Dirk Long, and Ahmad Pesaran at NREL
- Eric Darcy at NASA

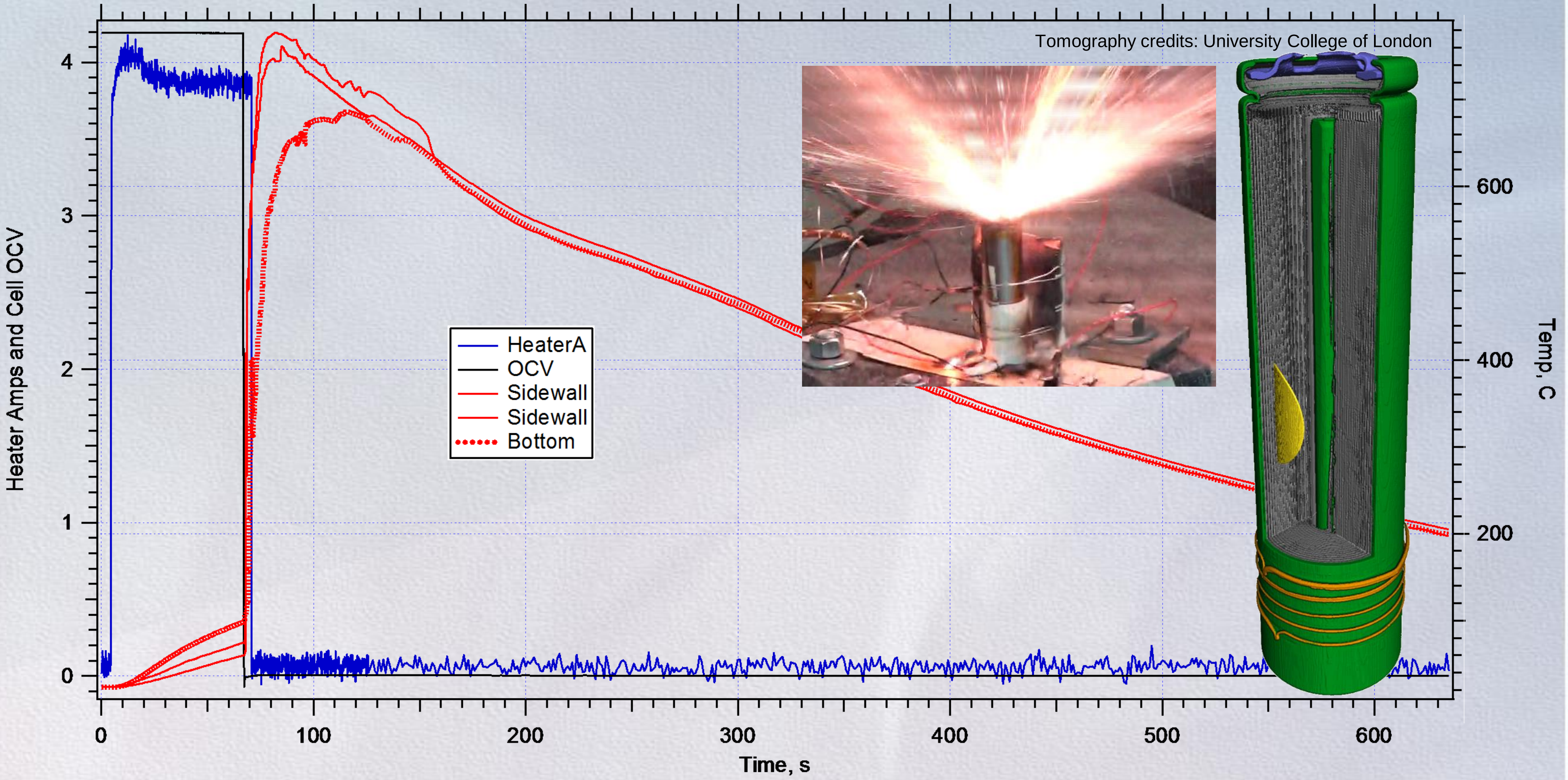
US Patent # 9,142,829

Wax formulation used melts ~57°C

Thin (10-20 μm) wax layer is spin coated on Al foil pad

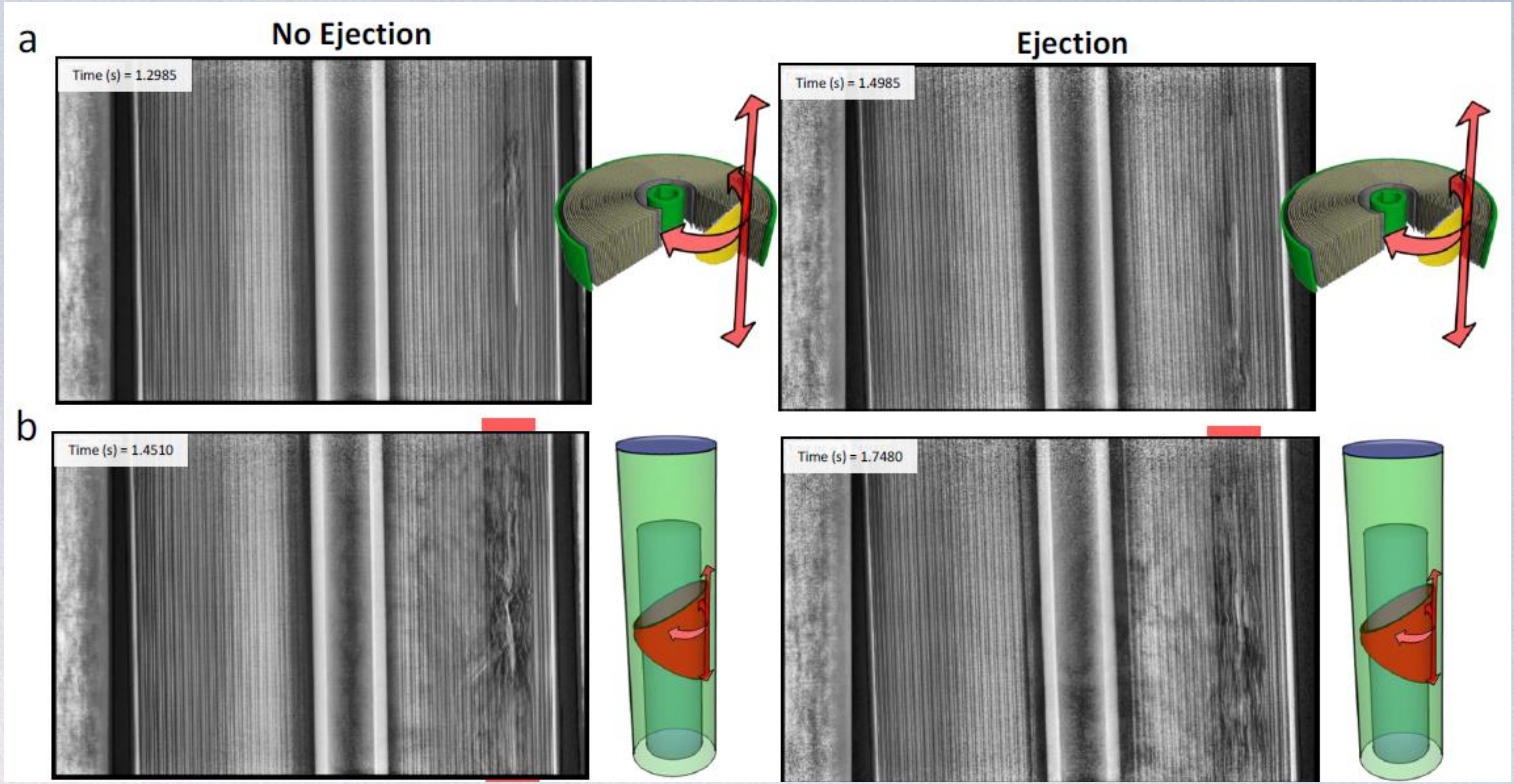
You're a 2016 R&D 100 Finalist

Single Cell TR – Moli 2.4Ah with ISC Device



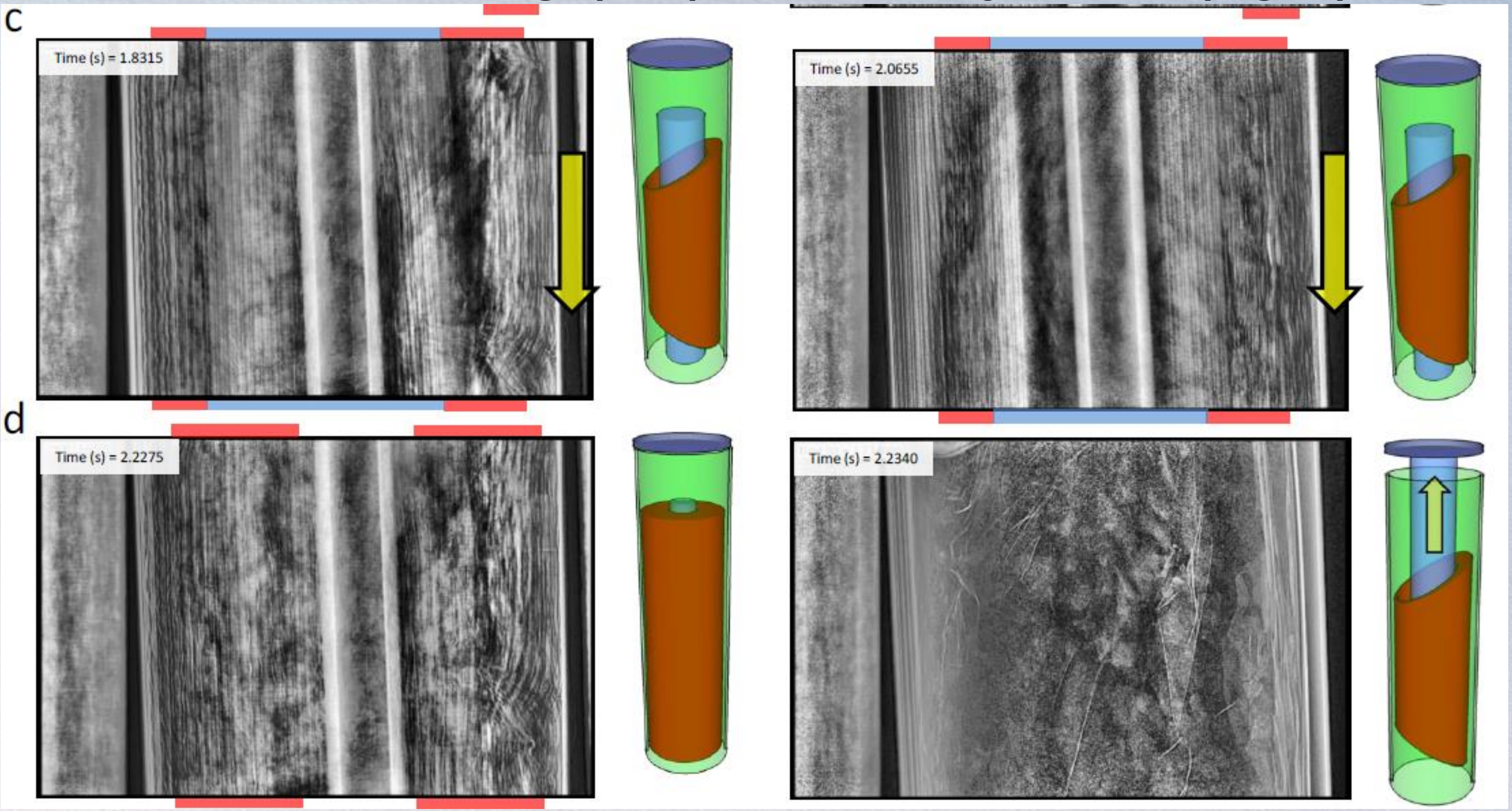
Open air test with cell charged to 4.2V and with TCs welded to cell side wall (2) and bottom (1)

High Speed 2D X-ray Video of ISC Device



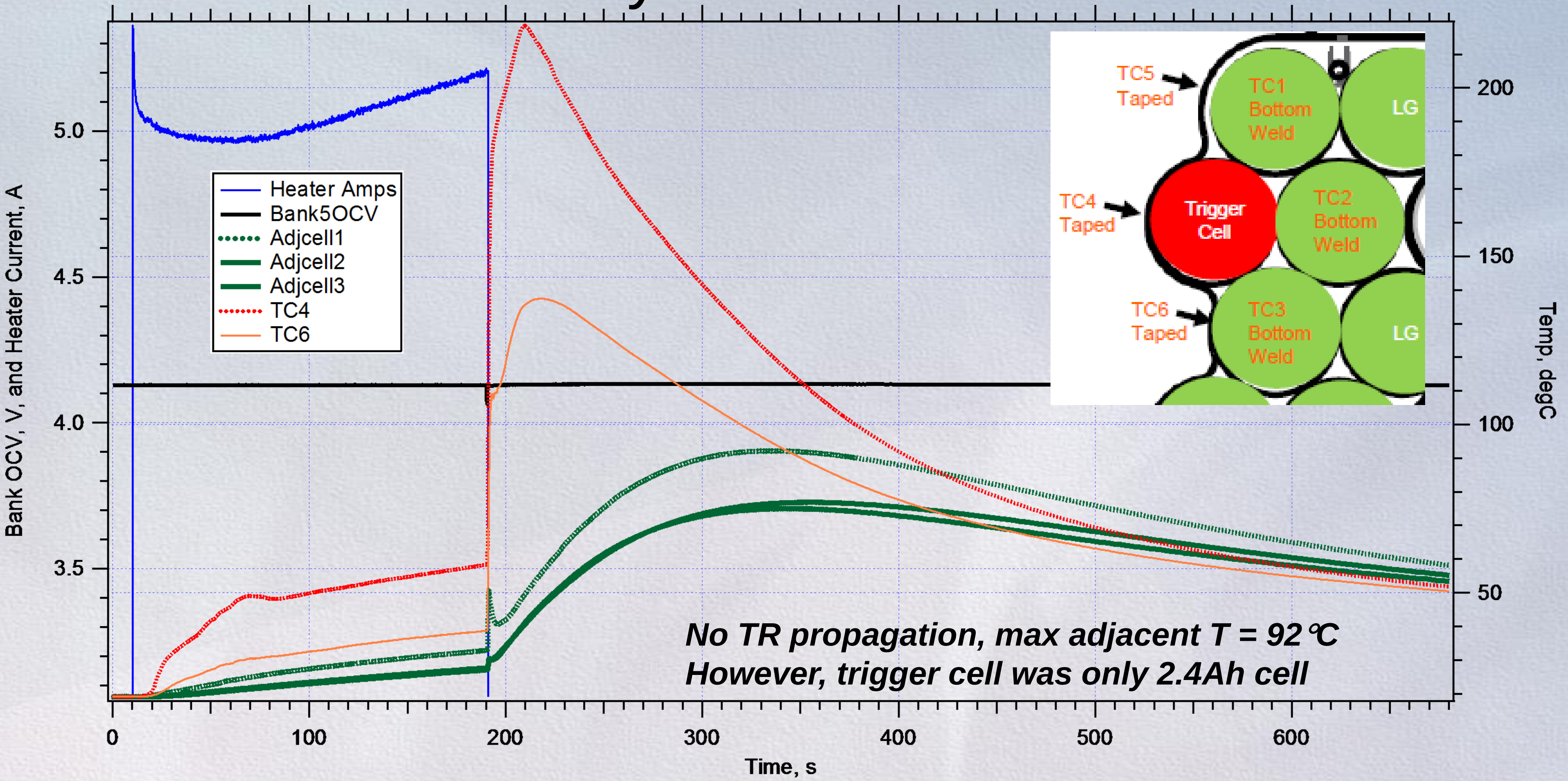
Stages of thermal runaway progression with the ISC device resulting in (left) nominal venting and (right) ejection of JR

Nominal venting (left) and JR ejection (right)



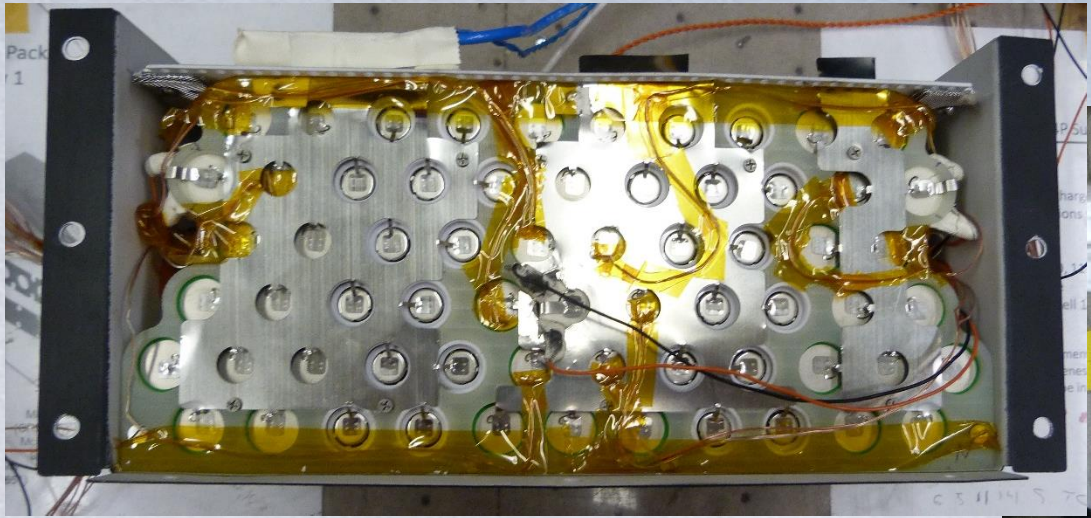
Finegan, D, et. al., “Understanding Battery Failure: A Multi-Scale and High-Speed X-ray CT Approach” Poster #250, IMLB 2016, Chicago, IL

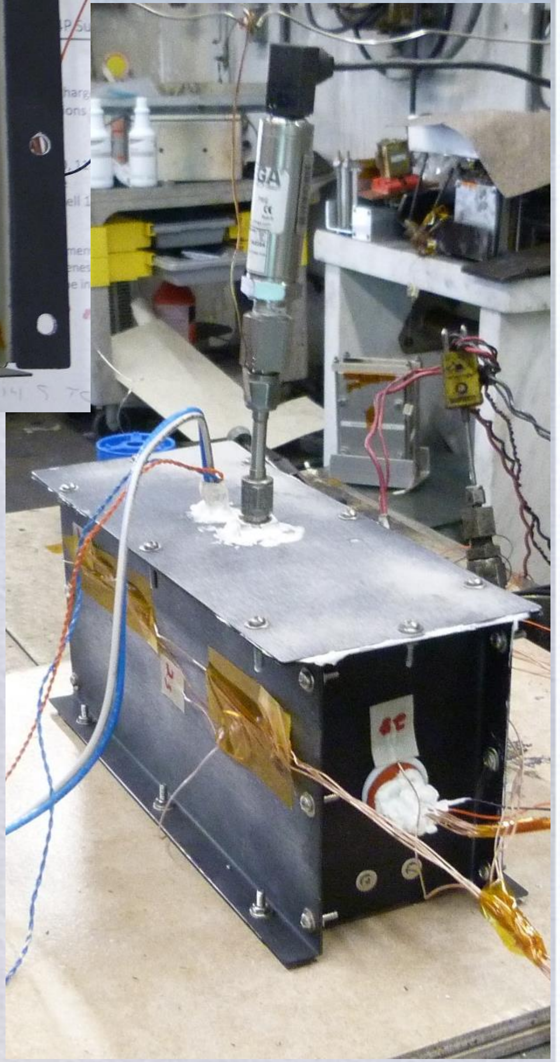
Full Scale Battery TR Test – MoliJ ISC Cell



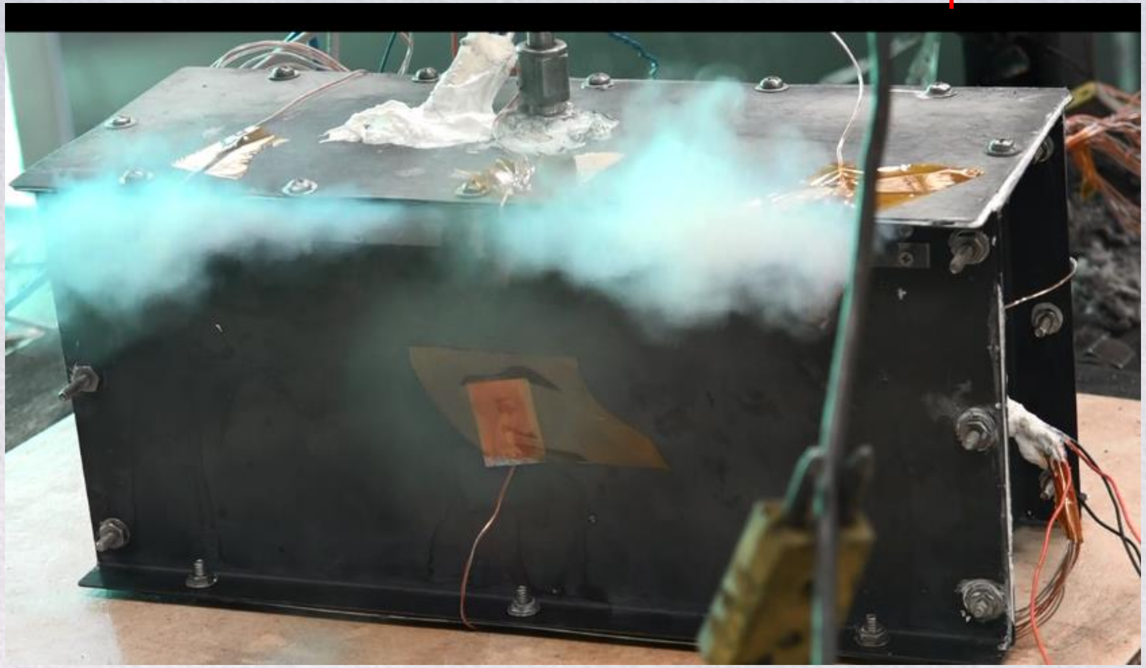
Heater power ~42W for 180s. Onset of TR (OTR) occurs 180s after power on and coincides with trigger bank OCV dip.
Adjacent cell1 has ΔT = 58.9°C to max of 92.0°C, while adjacent cells 2 & 3 have ΔT = 48°C to max of 76.0°C

No TR Propagation, Only Smoke Exits Battery



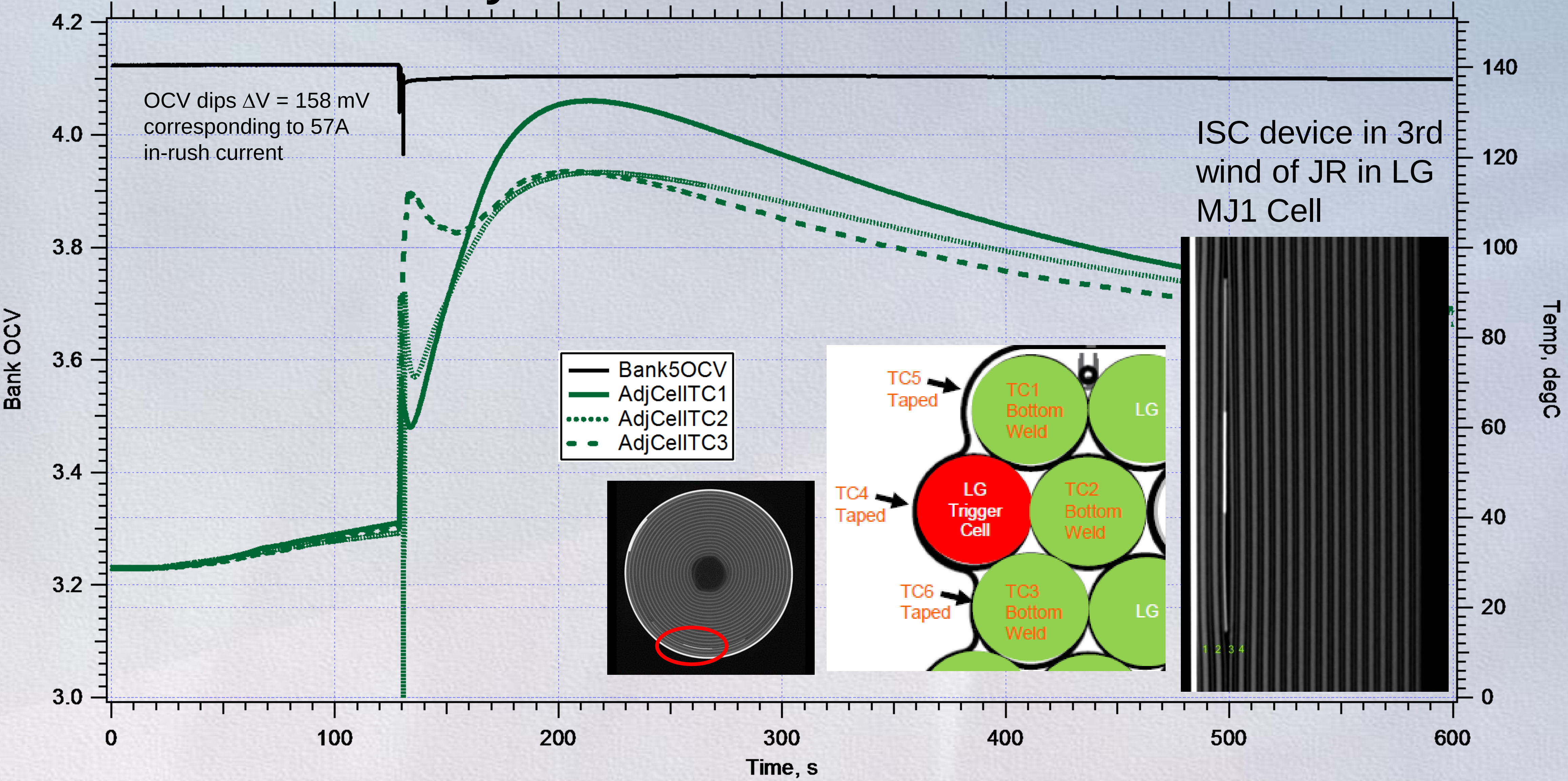


Mesh 40 & 30 steel screens arrest flames and sparks



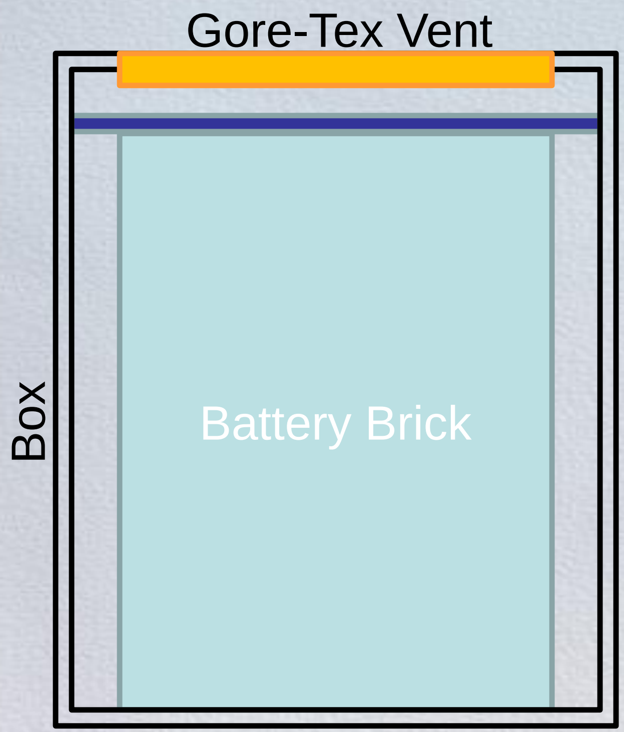
However, trigger cell was only 2.4Ah cell

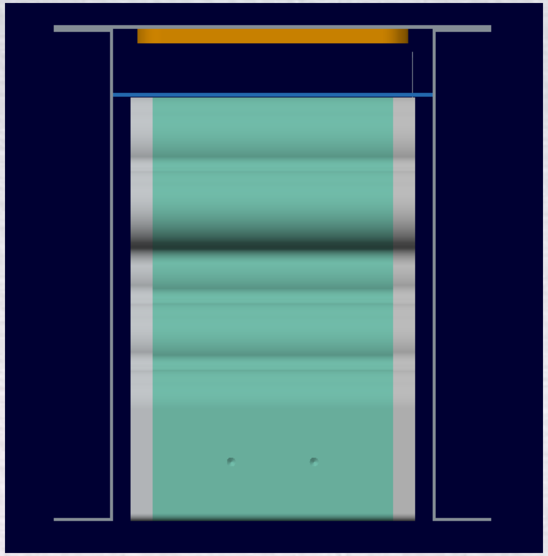
Full Scale Battery TR Test – 3.5Ah LG MJ1 ISC Cell



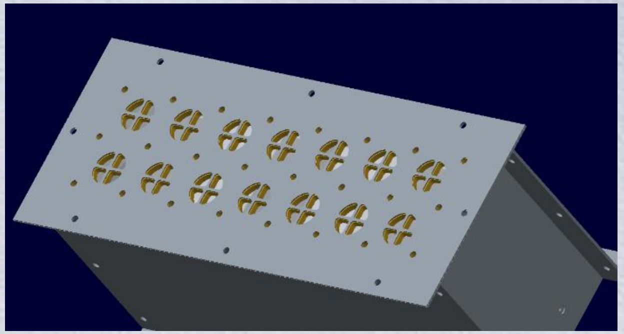
Adjacent cell temperatures TC1, TC2, and TC3 peak at 133°C, 117°C, and 117°C in 77-87s from onset temperatures of 39°C, 37°C, and 38°C for ΔT = 94°C, 77°C, and 78°C, respectively.

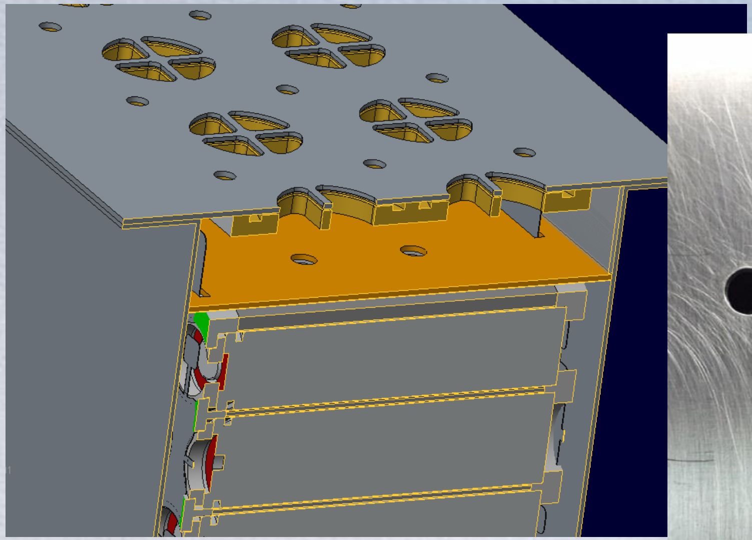
Added Gore Fabric Vent – Design Details

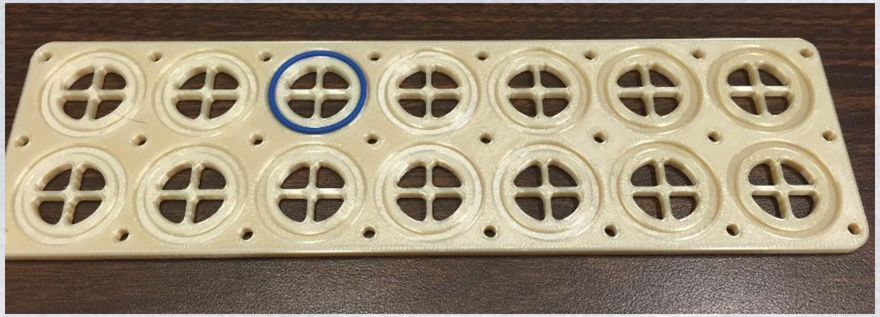




Inside lid with flame arrestors



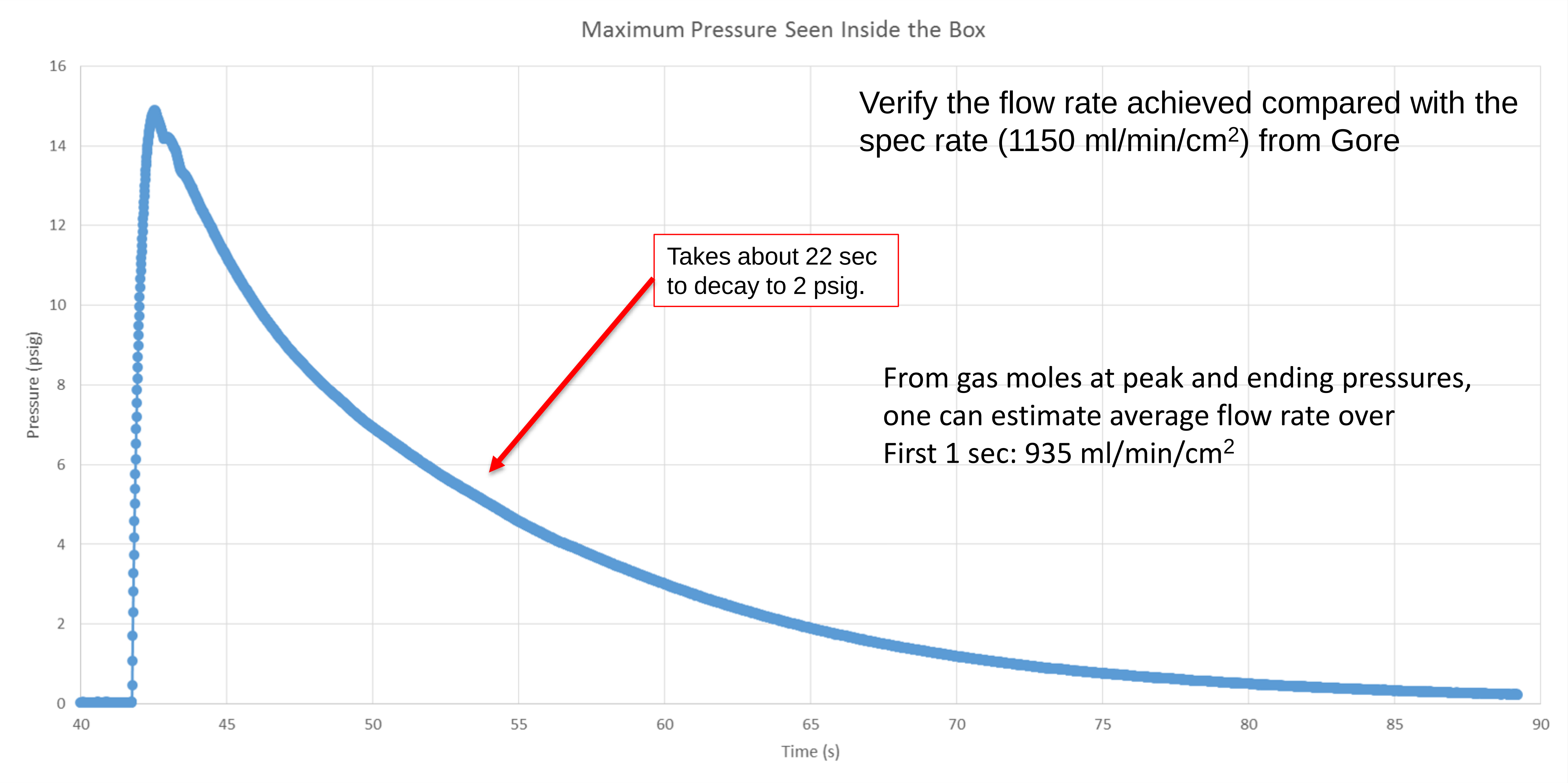




3D printer plastic for the Gore backer plate

- We will test if the box can hold pressure with an air test before we do battery test
- New boxes with slightly increased void volume and wall thickness are in

Gore Vent Testing

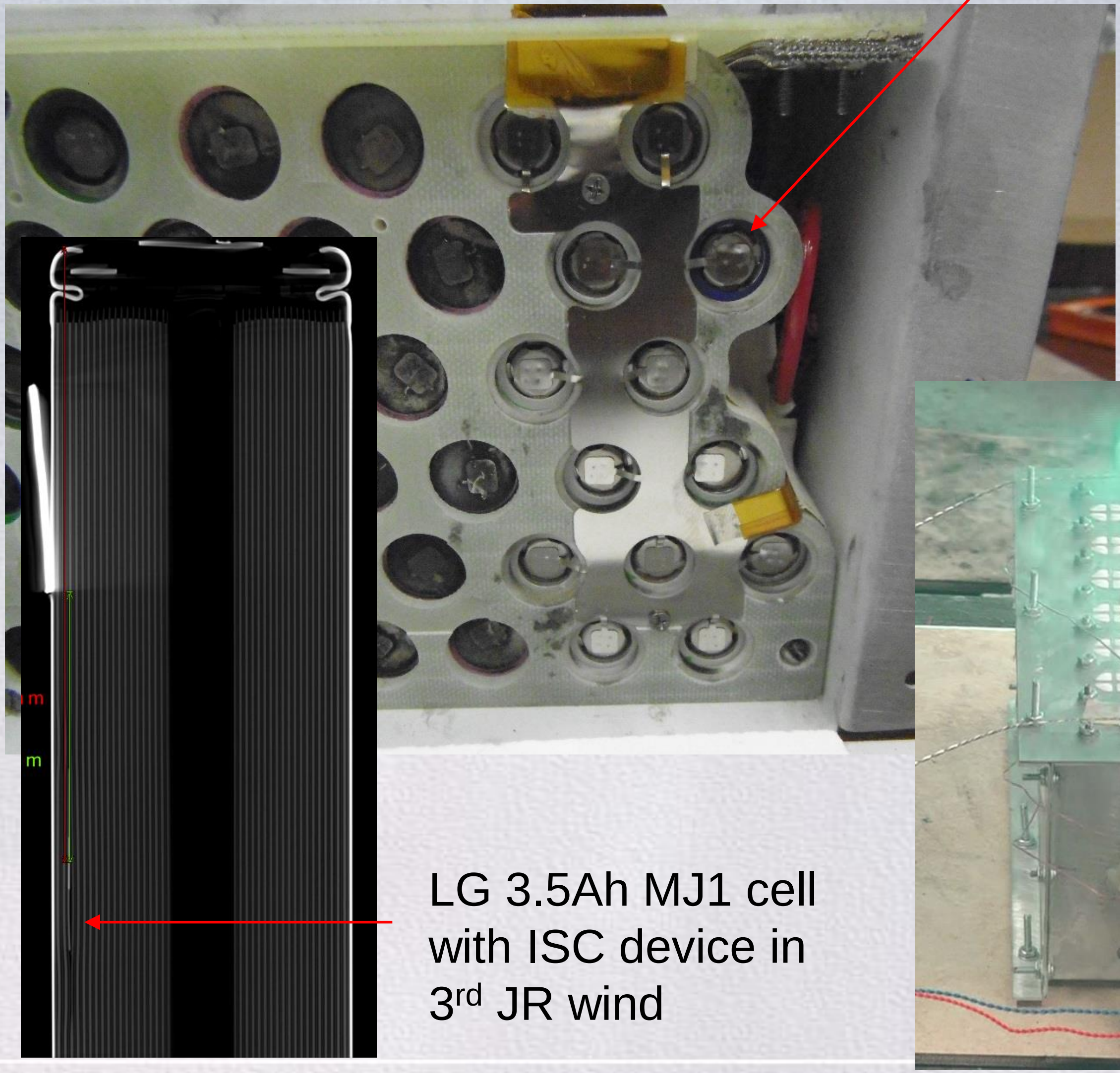


Verify the flow rate achieved compared with the spec rate (1150 ml/min/cm^2) from Gore

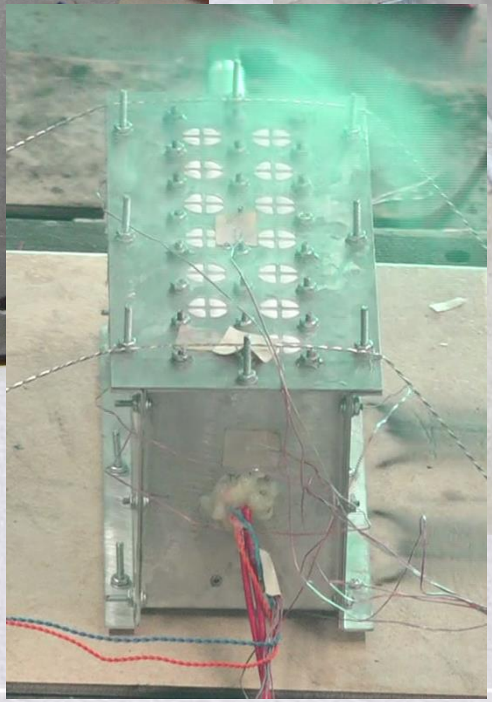
From gas moles at peak and ending pressures, one can estimate average flow rate over First 1 sec: 935 ml/min/cm^2

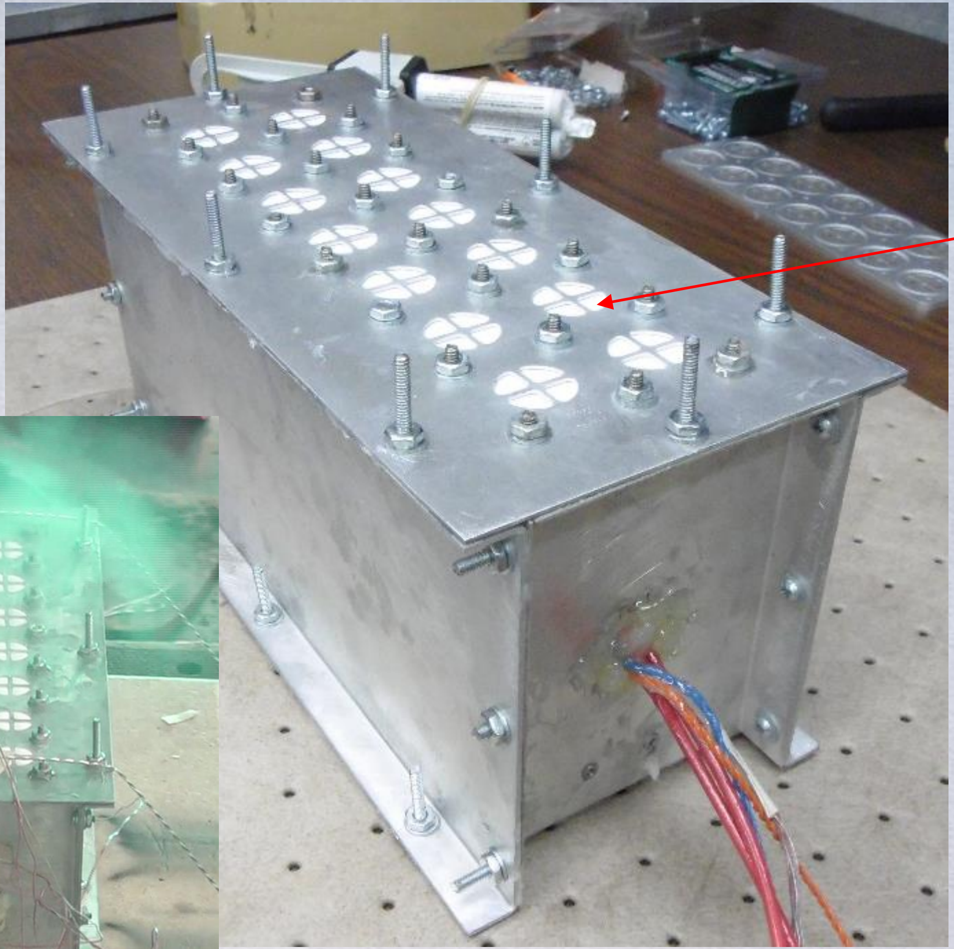
No TR Propagation – Only Clean Smoke Exits Gore Vent

LG MJ1 ISC device trigger cell (3.5Ah)



LG 3.5Ah MJ1 cell with ISC device in 3rd JR wind





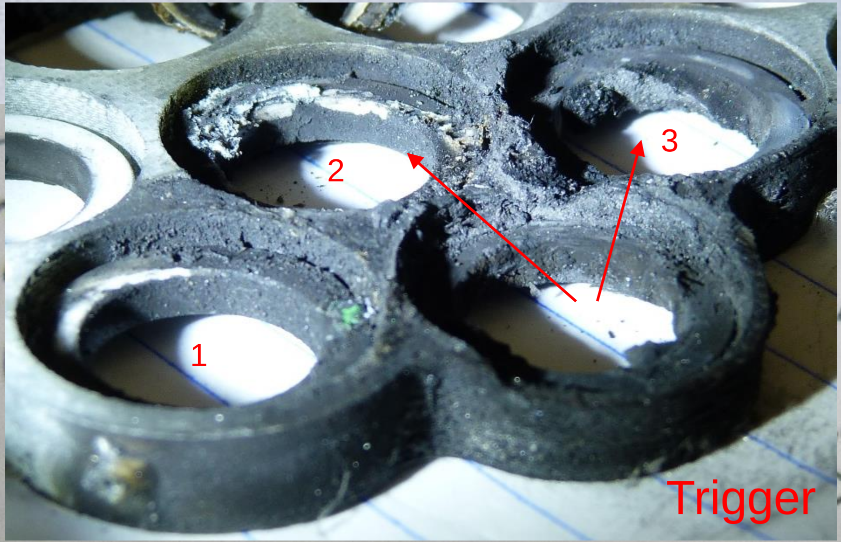
Gore fabric Vent design

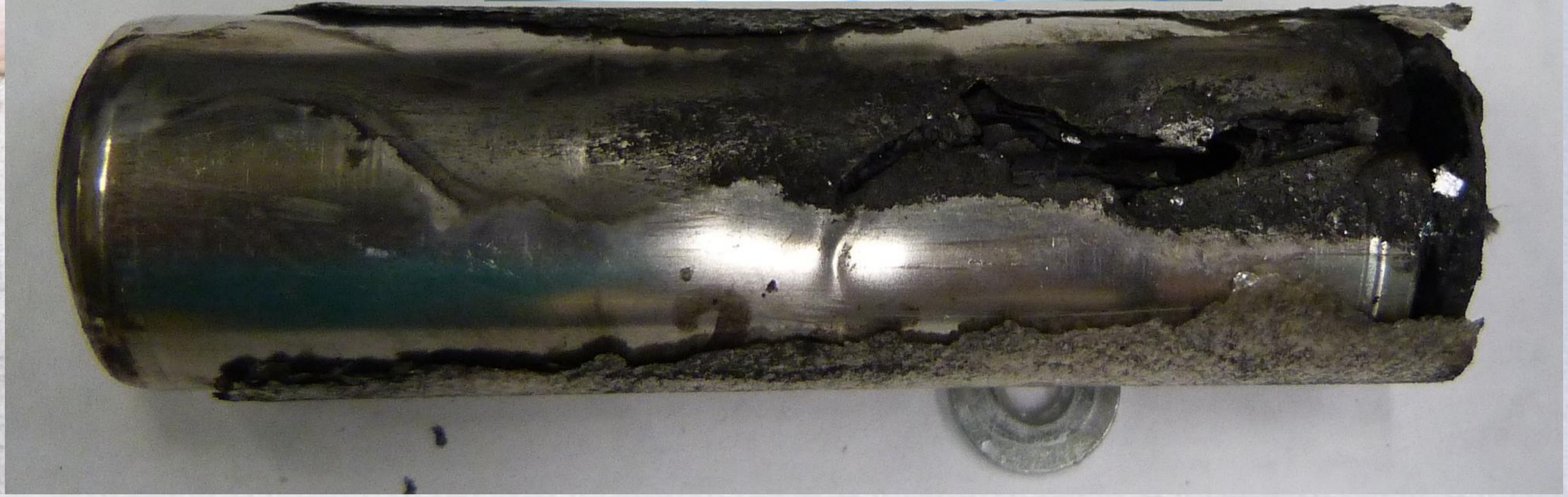
Battery bottom edge seal fails and relieves internal pressure at ~11.4 psig (0.77 bar)

3.5 Ah Trigger Cell Experienced a Side Wall Rupture

Trigger cell was a struggle to extract from heat sink.
The mica insulation was severely damaged adjacent to rupture

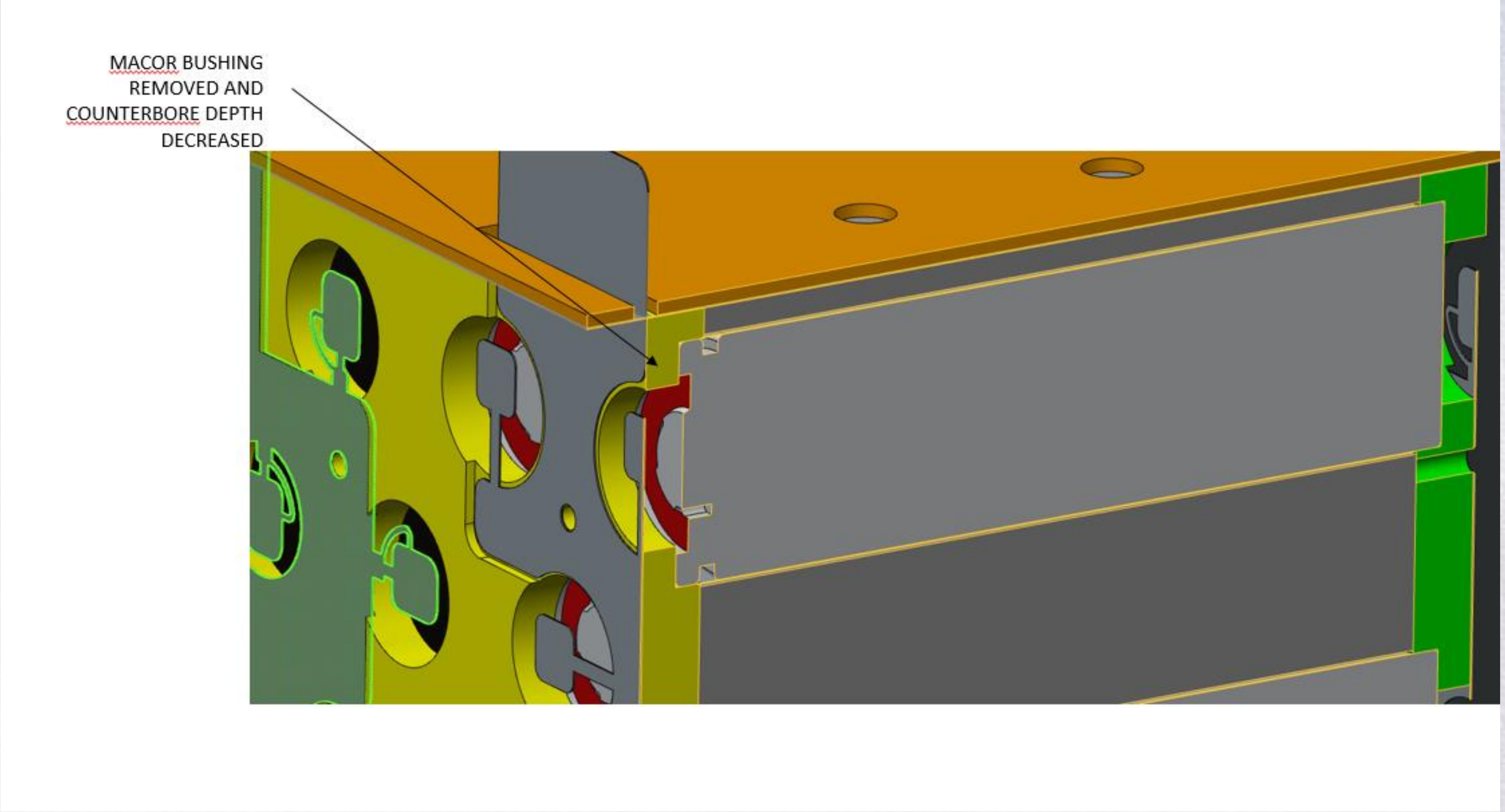
Cell	OCV (V)	Mass (g)
Trigger	0	17.161
1	3.474	46.801
2	0.336	46.691
3	0	46.671

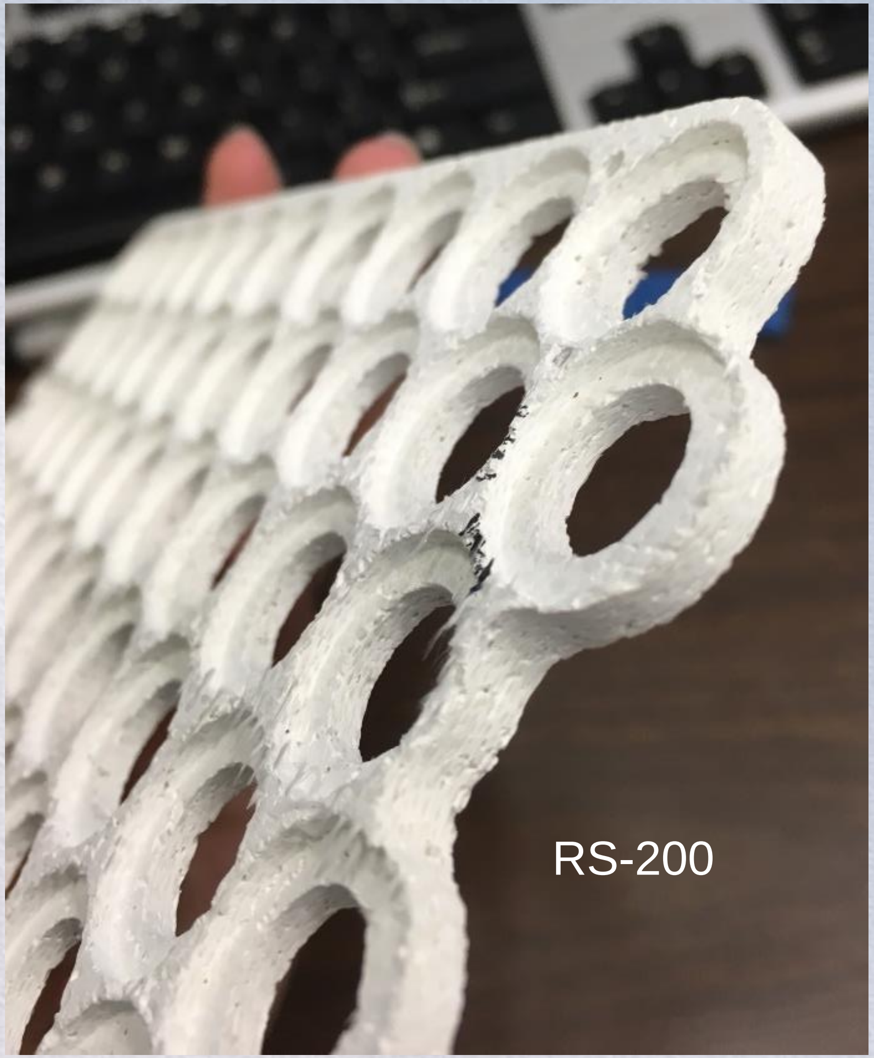




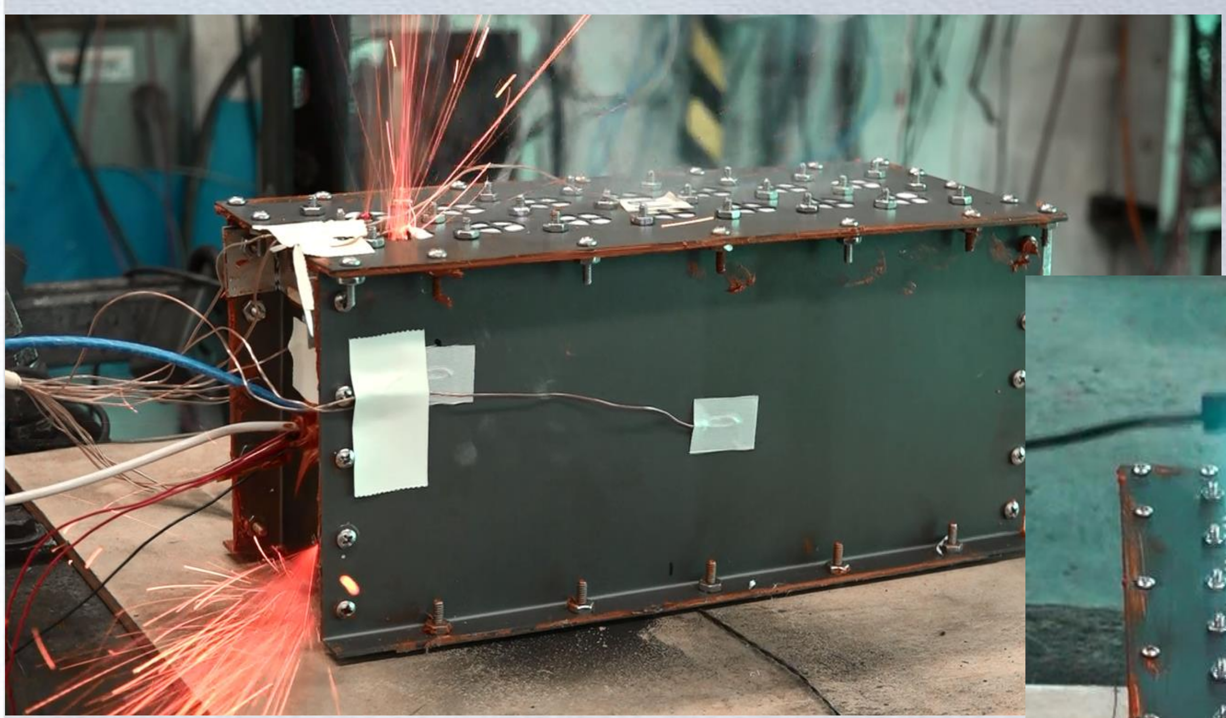
Zircar RS-200 Refractory Material

- Can it withstand a side wall rupture?
  - Replace the G10/FR4 capture plate and Macor® ceramic bushings with a redesigned RS-200 capture plate
  - Downside is that its harder to machine and not as strong

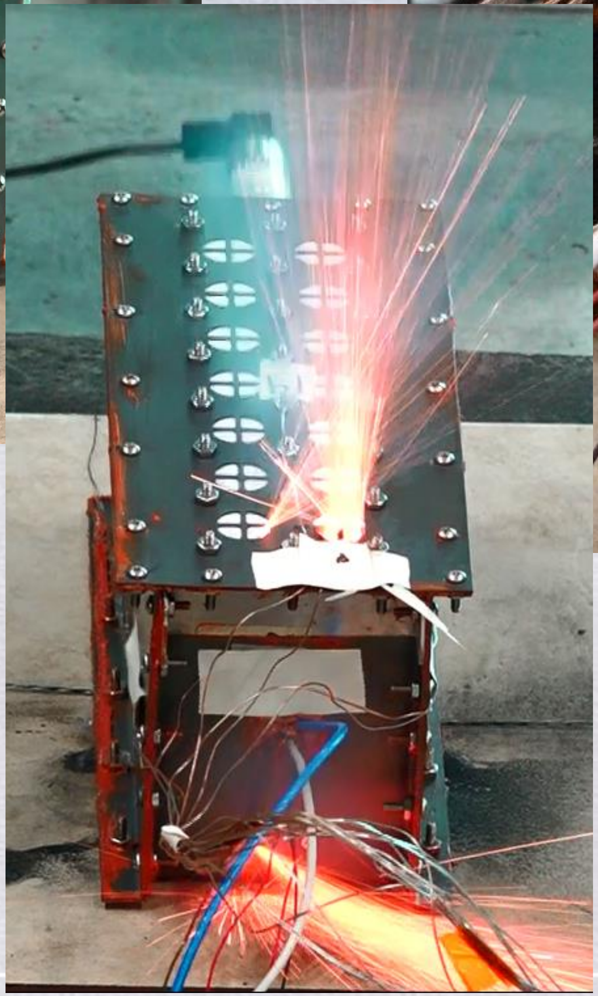


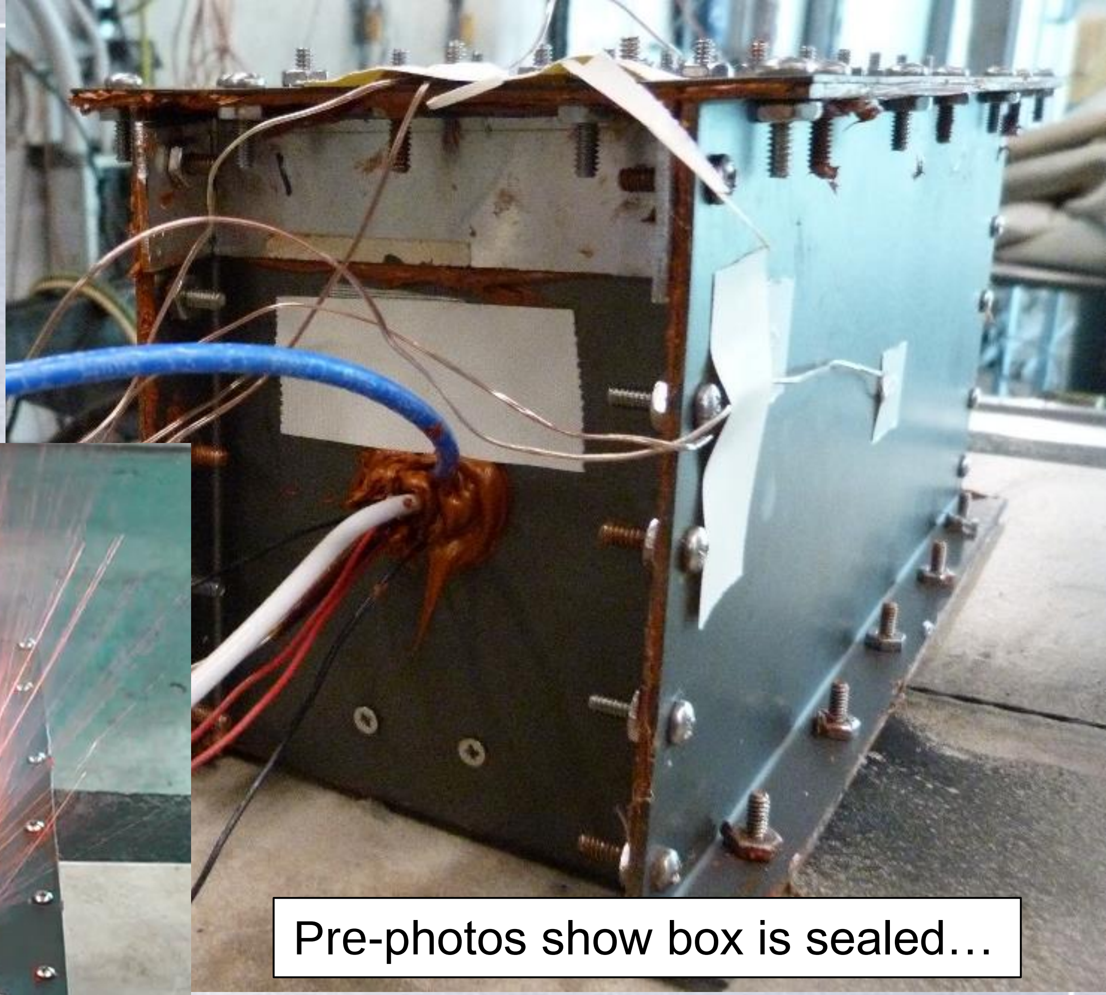


Test Photos



Flames exiting from top and sides of box, less than 1 second

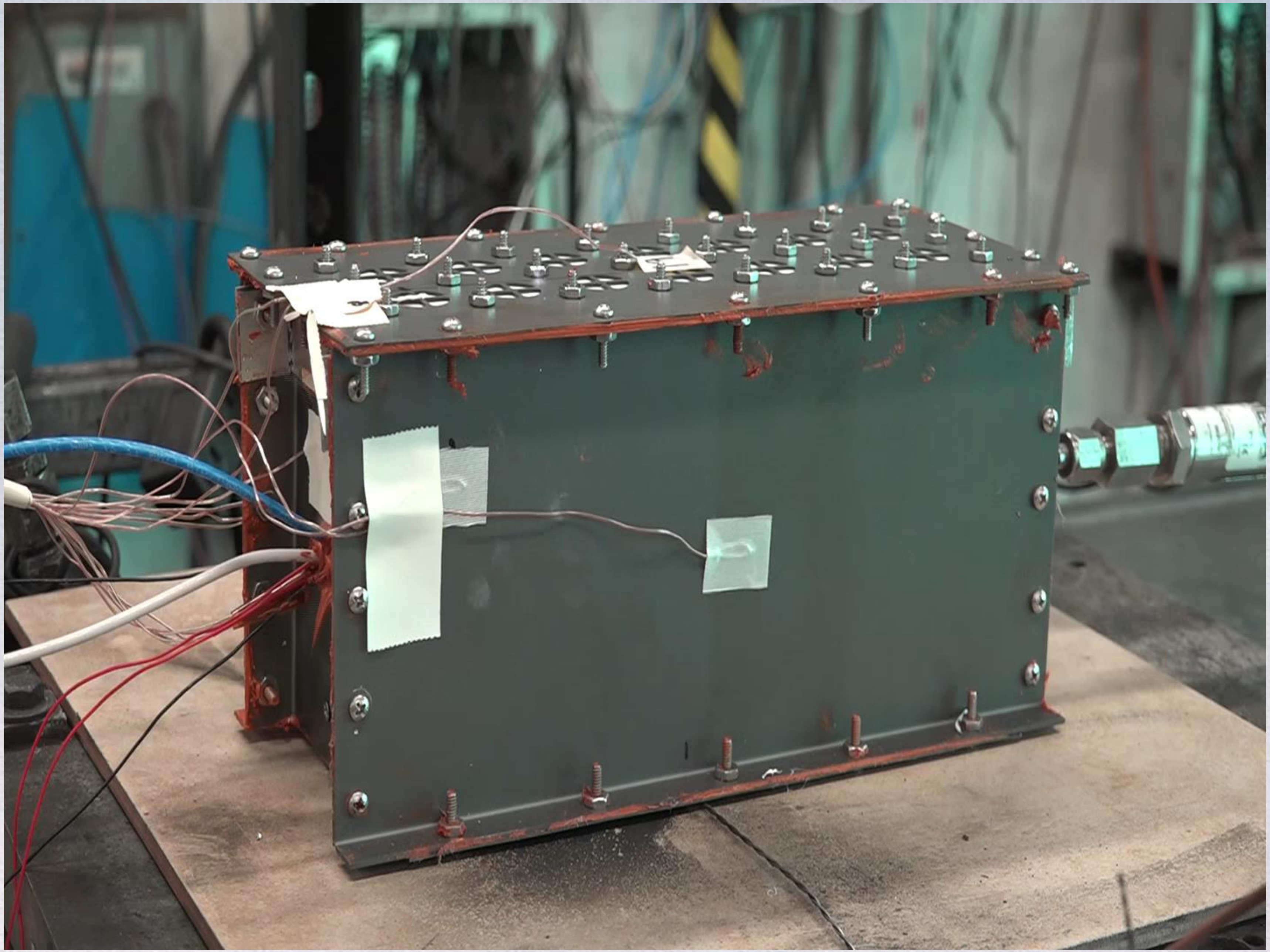




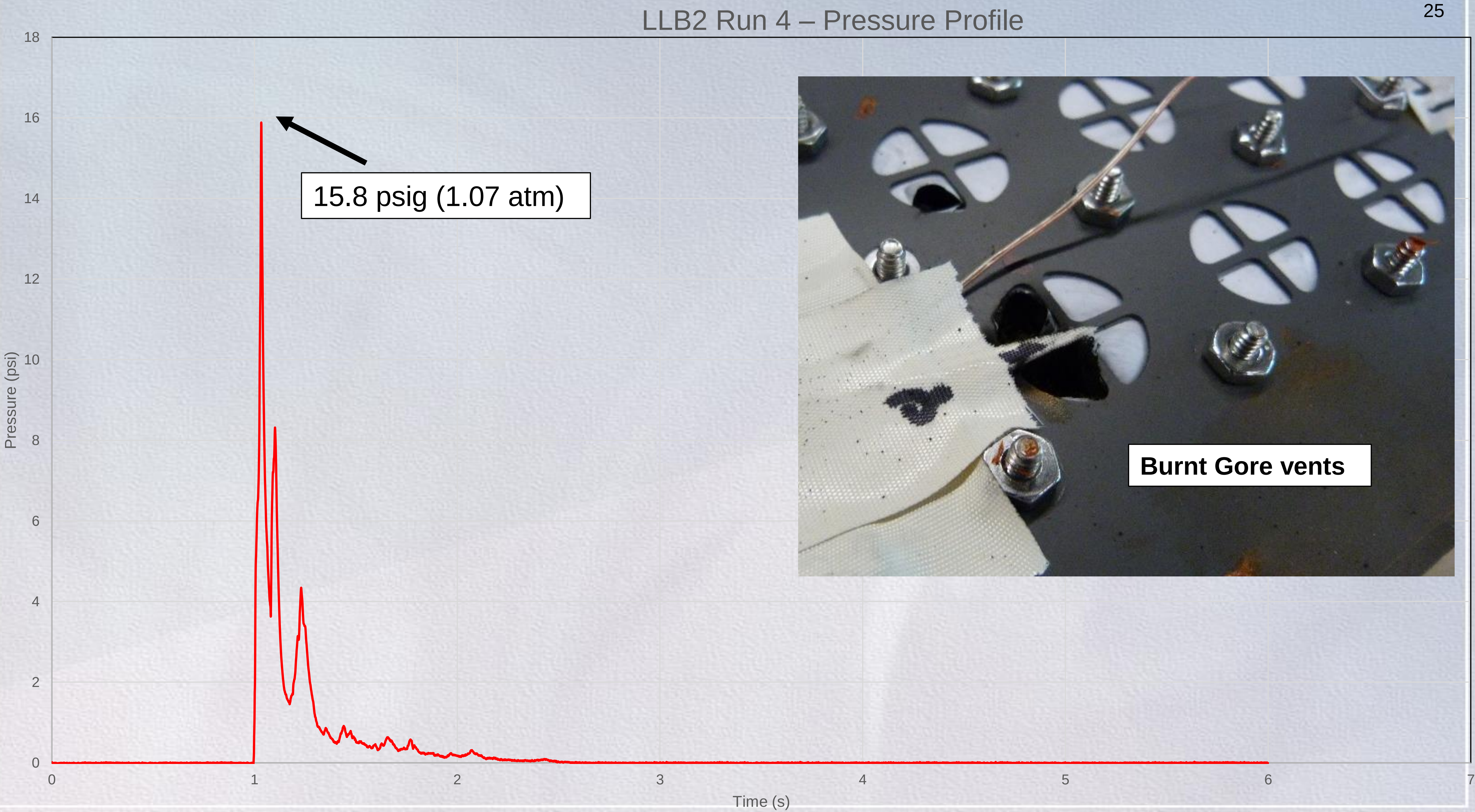
Pre-photos show box is sealed…

Cell flame path was insufficiently tortious and sparks burn through 2 Gore vents

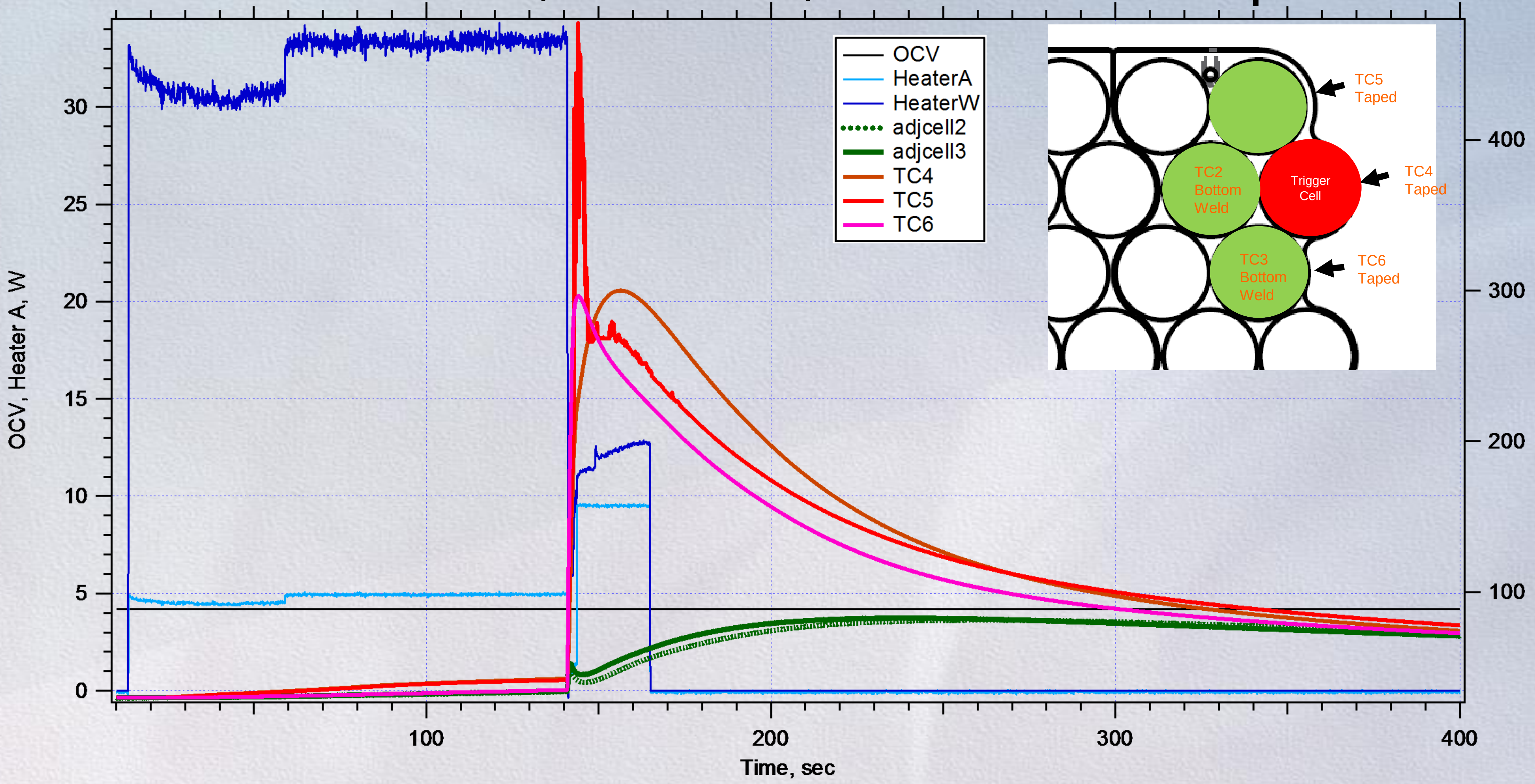
Not enough sealant on screw and hole

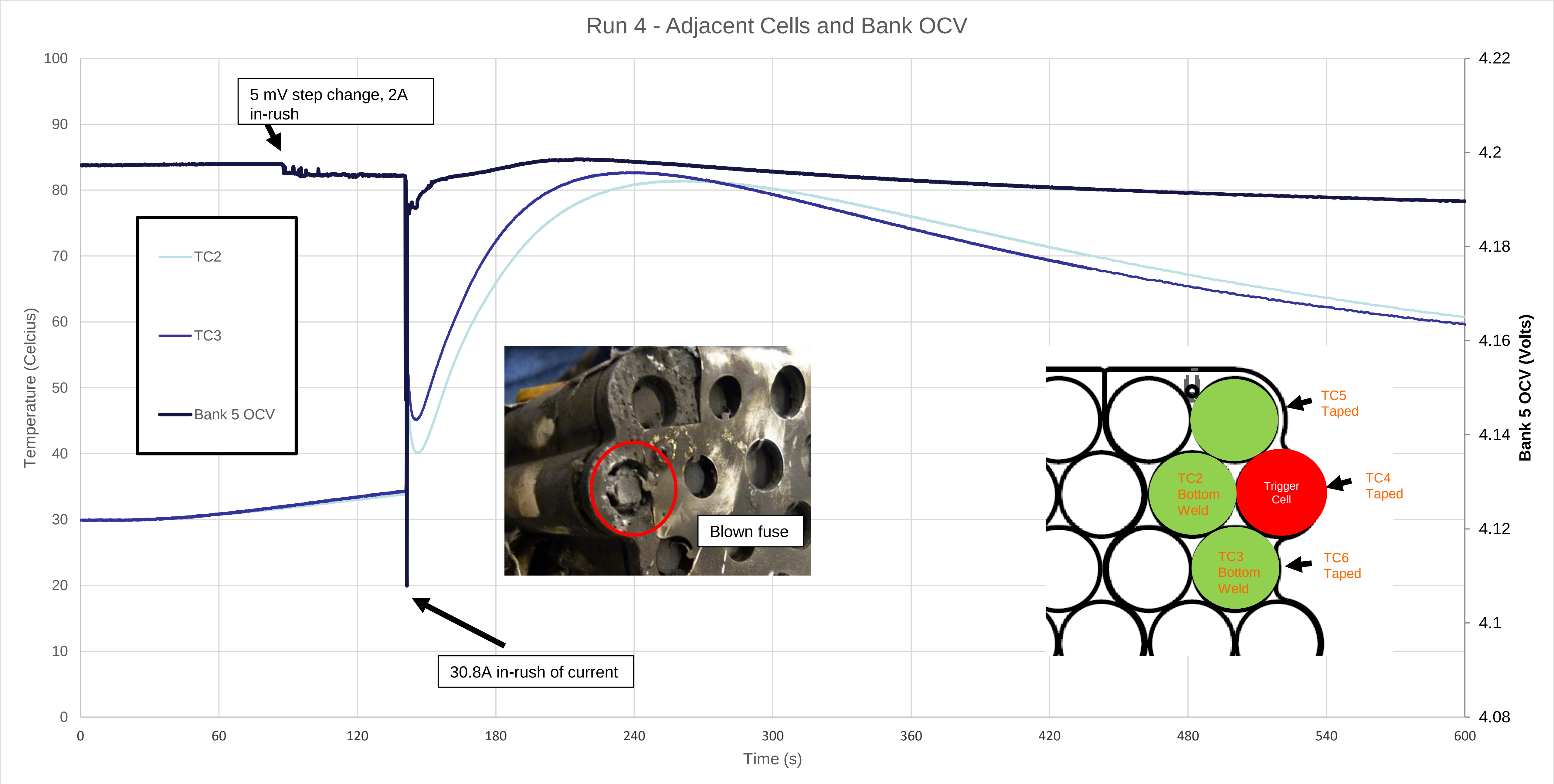


Test Video


LLB2 Run 4 – Pressure Profile
15.8 psig (1.07 atm)
Burnt Gore vents
Pressure (psi)
Time (s)
0
2
4
6
8
10
12
14
16
18
0
1
2
3
4
5
6
7

Run 4 – OCV, Heaters, & Interior Temps

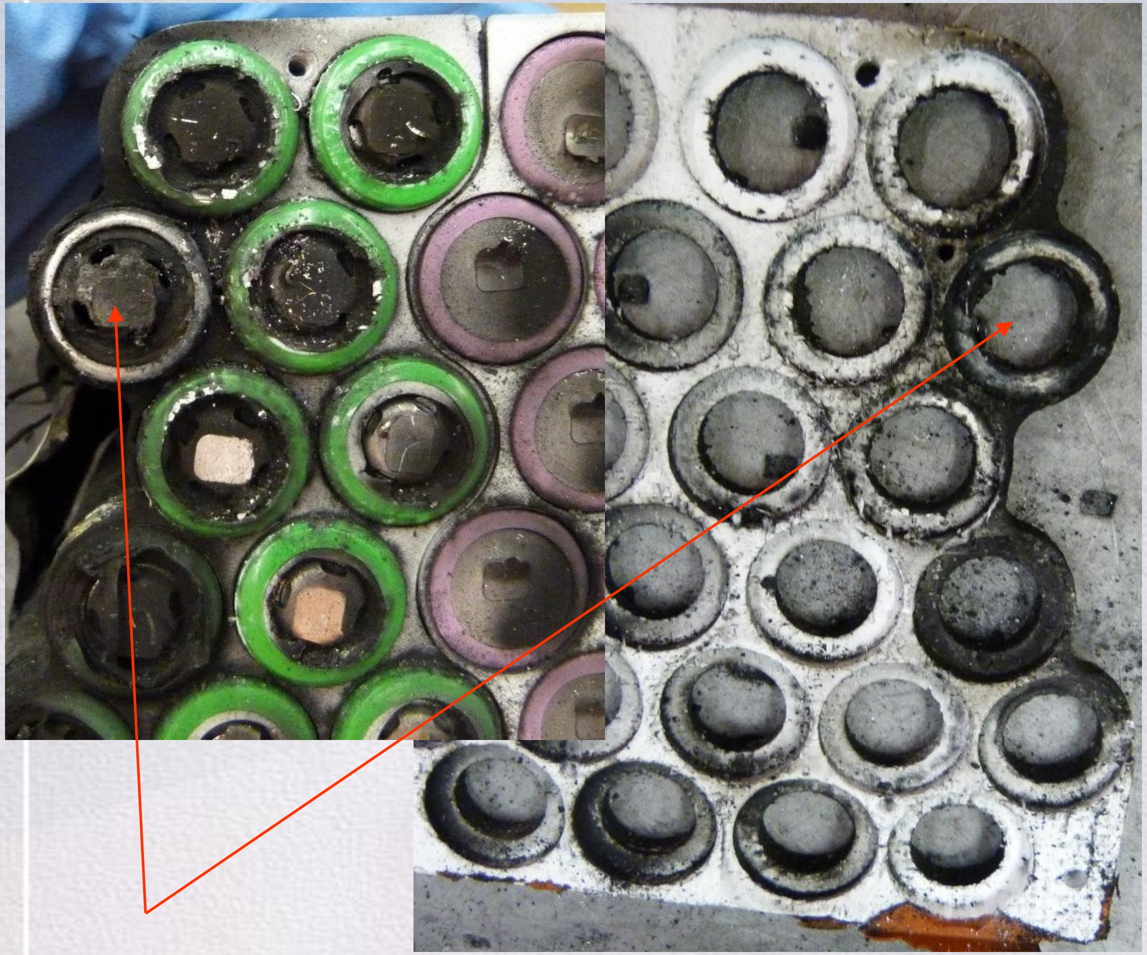




TC2 and TC3 peak at 81°C and 83°C from onset temperatures of 34°C and 35°C respectively. ΔT = 46°C after 111s and 47°C max after 97s.

Post-Test Photos

Zircar capture plate held up well



Trigger cell location

G10 damage

Post-Test Photos – Trigger Cell

Post-Test Mass: 25.3g

Bottom breach

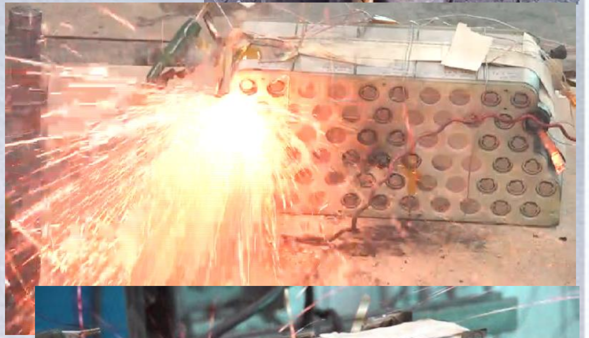
Spin groove is stretched

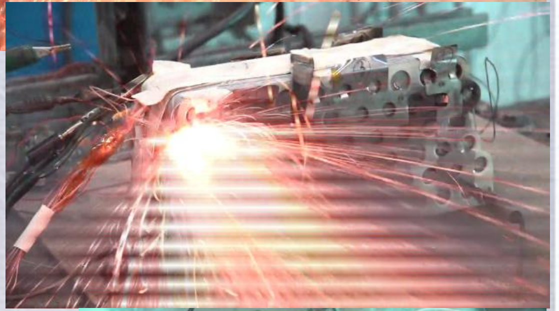
Run 4 Findings

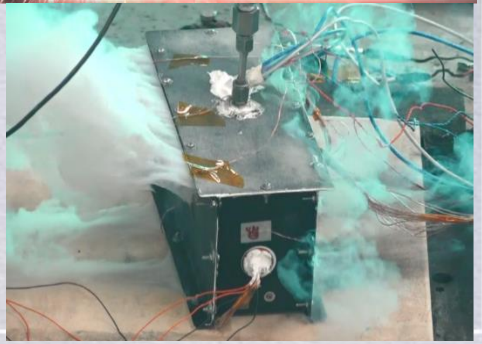
- ISC device in 3.5Ah LG cell triggered in 127 seconds with bottom heater at 32W average
  - Very similar initiation time (run 3 in 119s)
  - Very similar biasing of adjacent cells (34-35°C) at onset of TR (run 3 at 37-39°C)
- No propagation of TR
  - Despite bottom rupture of trigger cell, which damaged the G10/FR4 negative capture plate
  - Heat sinks were undamaged
- Max adjacent cell temperatures < 83°C
  - Adjacent cell temperature rise was 46-47C, significantly lower than run 3 (77-94°C)
  - Bottom rupture is less severe than side wall rupture
- Zircar positive capture plate held up well
  - Still need to figure how to achieve a manufacturable design for this part
  - Need it on both ends of the cell
- New box sealant and added fasteners were a significant improvement
  - 2 of the 14 gore vents were perforated by the pressure pulse and allowed the release of sparks for about 1s
  - 15 psig (1 atm) peak was measured before the failure
    - Gore vent is rated to 25 psig (1.7 atm)
- Design guidance for LLB2 flight project
  - Increasing the Al heat sink spacing between cells beyond 0.5mm will increase safety margins
  - Thermal modeling indicates that increasing heat sink spacing is better than increasing mica cell sleeve thickness

Spacesuit Prototype Battery Test Summary

- Al Heat Sink Tests
  - 4 attempts to drive > 250Wh/kg cell into TR – All failures
    - 2 with Panasonics, 2 with LGs, all with home made bottom heaters
  - 5 attempts with MoliJ ISC device cells – No propagation of TR
    - 1 dud and 4 success with the MoliJ ISC cell driven into TR
  - 2 heat to vent tests with 5 fully charged LG cells each
    - No side wall ruptures in areas supported by the sink
- LLB2 brick tests (All 6 MoliJ ISC cells successfully driven to TR)
  - 3 no-Ni bussing brick tests
    - No TR propagation and no OCV changes to adjacent cells with excellent temp margins
      - Interior cell trigger ΔT ~ 19°C (one run)
      - Edge cell trigger ΔT ~ 42°C (two runs)
    - Interior cell trigger are less vulnerable than edge cells based on temperature rise (max-onset T) on adjacent cells
  - 3 Ni bussing (13P5S)
    - No propagation of TR, no impact on adjacent cell OCVs
    - Very good temperature margins (vs onset of TR temperature)
      - Interior cell trigger: ΔT ~ 30°C (one run)
      - Edge cell trigger ΔT ~ 48°C (one valid run)
- LLB2 full scale tests (4 runs – 2 with MoliJ, 2 with LG MJ1 ISC implanted cells)
  - No propagation of TR (even with side wall rupture in of LG trigger cell in Run 3)
  - Maximum adjacent cell temperature rise with MoliJ was 55-58°C
  - Maximum adjacent cell temperature rise with MJ1 was 94°C w/ side wall rupture and 46°C with bottom rupture
  - Gore vent design needs more flame arresting protection to handle MJ1 TR output
  - Screened vents were demonstrated as a successful flame arresting solution







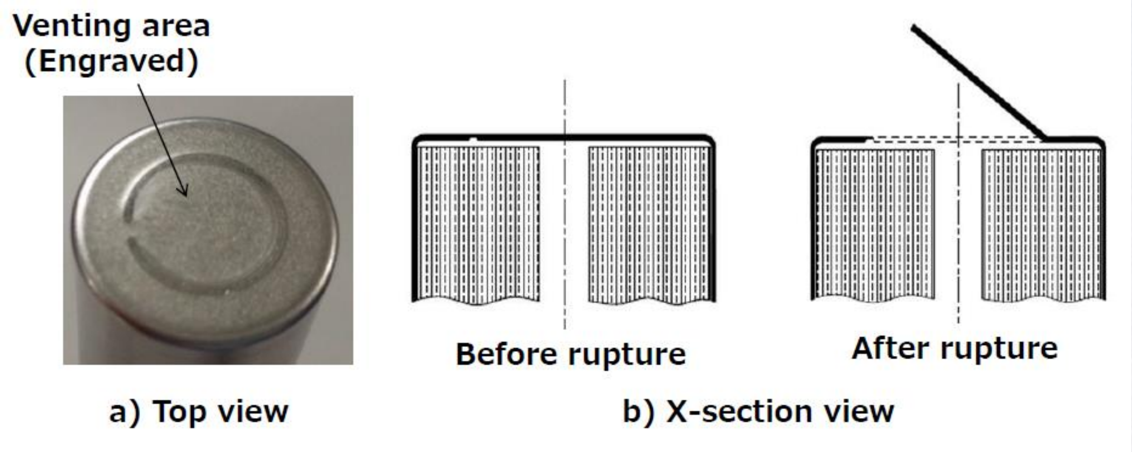
ISC Device Reveals Side Wall Rupture Risk

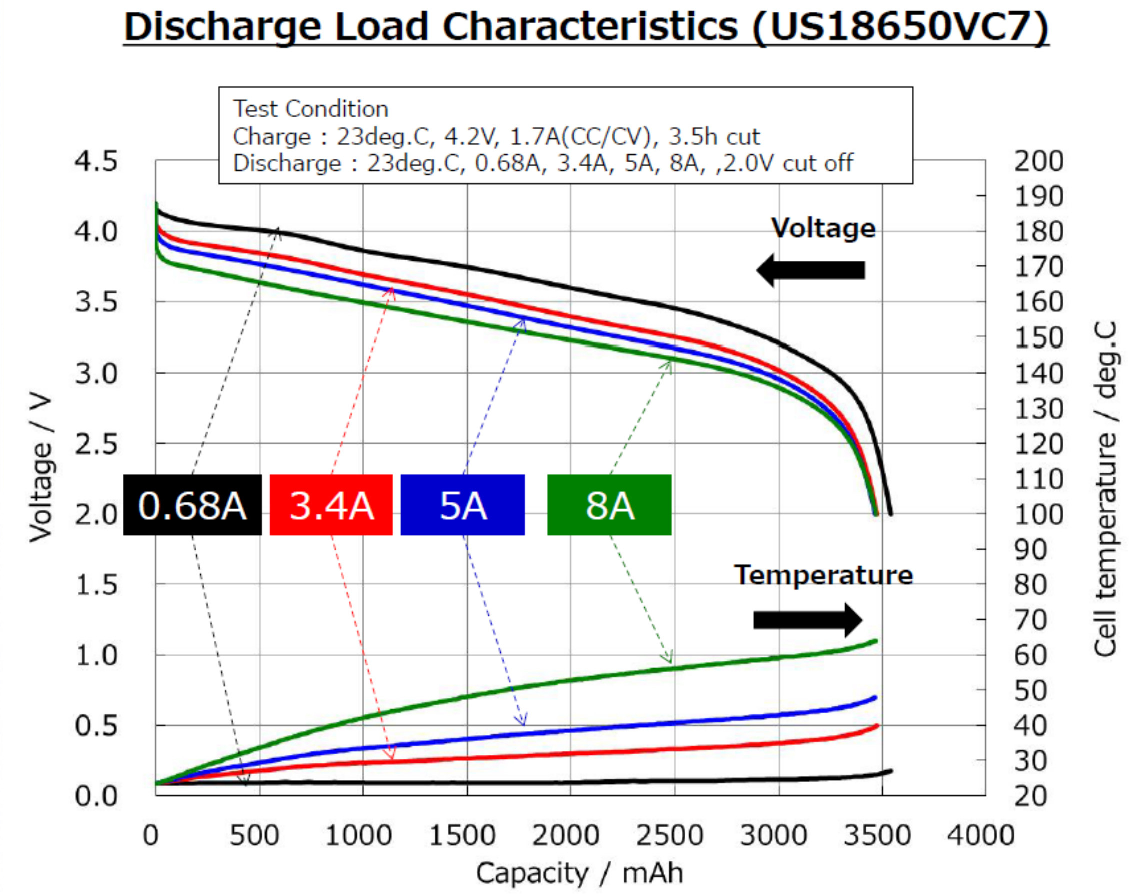
- LG MJ1 has thicker cell can
  - 165-175 microns
    - vs125 microns for NCR18650A or B
- Unsupported oven heating test
  - No side wall ruptures (30 cells)
  - Slow external heating to TR
- With ISC device (7 tested so far)
  - 5 sidewall ruptures
  - 1 bottom rupture

Photo credit: D. Finegan, University College of London

Investigation of Bottom Vent Cell Designs

Sony US18650VC7 Cell Design





This feature could greatly reduce the risk of side wall rupture during thermal runaway

Summary Findings

- ISC device enables critical battery safety verification
  - With the aluminum interstitial heat sink between the cells, normal trigger cells can't be driven into TR without excessive temperature bias of adjacent cells
  - With an implantable, on-demand ISC device, TR tests show that the conductive heat sinks protected adjacent cells from propagation
    - Very well protected (max T < 92°C) with a 2.4Ah cell design
    - Marginally protected (max T < 133°C) with a 3.5Ah cell design
    - Interior cells are more protected than edge or corner cells
  - LG MJ1 shown susceptible to side and bottom rupture with ISC device
    - Despite, no side wall ruptures during slow heat to vent testing (unsupported, 30 cells tested)
- High heat dissipation and structural support of Al heat sinks show high promise for safer, higher performing batteries
  - Battery brick design achieving > 190Wh/kg demonstrated to be safe
  - Battery design that doesn't emit flames or sparks achieves > 160 Wh/kg
- Future work
  - Will examine merits cell design with bottom burst disk vent feature to reduce side wall rupture risk
  - Refractory material for the capture plate to better protect adjacent cells from TR ejecta
  - Vaporizing heat sink as alternative to Al interstitial material

- Acknowledgements
  - M. Shoesmith, E-one Moli Energy for successfully implantation of ISC device in their 2.4Ah cell design
  - J.Y. Park, LG Chem for successfully implantation of ISC device in their 3.5Ah cell design